MODELLING THE IMPACT OF CLIMATE CHANGE AND DEVELOPMENT SCENARIOS ON EERSTE RIVER

by

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Declaration

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Abstract

This research investigated the impact of climate change and different development scenarios on the Eerste River, which is the primary source of water for Stellenbosch Municipality and the agricultural sector in the surrounding areas of Stellenbosch Town, South Africa. No climate change impact study, based on the latest emission scenarios, called Representative Concentration Pathways (RCPs), coupled with development scenarios, has been undertaken for the Eerste River.

The Pitman model was used to simulate the changes in the river flows and water demand in the catchment that could arise in the "near" (2022 to 2057) and "far" (2058 to 2093) future periods relative to the "present-day period" (1983 to 2018). The research included analysis of hydrological, land use, water consumption and statistically downscaled climate data projected by 11 Global Circulation Models of the Coupled Model Intercomparison Project - Phase 5 enforced by RCP 4.5 and RCP 8.5.

The results showed that climate change is expected to increase evaporation between 6% and 15%, and at the same time, causing rainfall to decrease between 2% and 8% in the future periods. This future climate is anticipated to cause a reduction in available water of between 8% and 18%, potentially triggering an increase in irrigation demand of between 12% and 29% in the future periods with a possible failure to meet the municipal water abstractions expected in the far-future period. It is expected that development scenarios could cause a net reduction in available water of between 2% and 3% in the Eerste River in the near-future period. This change in available water could be caused by an increase in municipal water abstractions of between 30% and 82% above the current capped water allocation of 7.224 Mm^3/a. At the same time, irrigation demand is unlikely to cause any additional impact on the Eerste River.

The combined impact of climate change and development scenarios indicated a reduction in available water of between 10% and 12% in the near-future period. The combined impact could cause a potential 12% increase in irrigation demand and failure to meet the municipal water demand between January and March based on the present-day abstraction pattern.

The overall impact of climate change and development scenarios on Eerste River flows would be a reduction in available water of between 2% and 18% in the future periods. Therefore, this research suggests increasing the capacity of existing farm dams and the promotion of water demand management activities to curb the potential impact of climate change and development scenarios on the Eerste River.

Opsomming

Hierdie navorsing het die impak van klimaatsverandering en verskillende ontwikkelingscenario's op die Eersterivier ondersoek, wat die primêre bron van water vir die Stellenbosch Munisipaliteit en die landbousektor in die omgewing van Stellenbosch, Suid-Afrika, is. Geen vorige klimaatsverandering navorsing, gebaseer op die nuutste emissiescenario's genaamd “Representative Concentration Pathways (RCP's)” tesame met ontwikkelingscenario's, is vir Eersterivier onderneem nie.

Die Pitman-model is gebruik om die veranderinge in die riviervloei en die vraag na water in die opvangsgebied wat in die “nabye” (2022 tot 2057) en “ver” (2058 tot 2093) toekomstige tydperke kan ontstaan, relatief tot die “huidige” (1983 tot 2018) tydperk te simuleer Die navorsing het ontleding van hidrologiese-, grondgebruik-, waterverbruik- en statisties afgeskaalde klimaat-data ingesluit, soos geprojekteer deur 11 wêreldwye sirkulasiemodelle van die “Coupled Model Intercomparison” projek - Fase 5 wat deur RCP 4.5 en RCP 8.5 voorgeskryf is.

Die resultate het getoon dat klimaatsverandering na verwagting die verdamping tussen 6% en 15% sal verhoog, en dat die reënval terselfdertyd tussen 2% en 8% sal daal in die toekomstige tydperke. Daar word verwag dat hierdie toekomstige klimaat 'n afname in beskikbare water van tussen 8% en 18% sal veroorsaak, wat moontlik 'n toename in die vraag na besproeiing van tussen 12% en 29% in die toekomstige tydperke kan veroorsaak, met die moontlikheid dat daar nievoldoen sal kan word aan die munisipale water aanvraag in die verre toekoms. Daar word verwag dat ontwikkelingscenario's 'n netto vermindering in beskikbare water van tussen 2% en 3% in die Eersterivier in die nabye toekoms kan veroorsaak. Hierdie verandering in beskikbare water kan veroorsaak word deur 'n toename in munisipale wateronttrekkings van tussen 30% en 82% bo die huidige beperkte toekenning van 7.224 Mm^3/a. Terselfdertyd sal die vraag na water vir besproeiing waarskynlik nie 'n bykomende impak op die Eersterivier veroorsaak nie.

Die gesamentlike impak van klimaatsverandering en ontwikkelingscenario's dui op 'n afname in beskikbare water van tussen 10% en 12% in die nabye toekoms. Die gesamentlike impak kan 'n moontlike toename van 12% in die besproeiingsvraag veroorsaak en daartoe lei dat die munisipale watervraag tussen Januarie en Maart nie bevredig kan word nie, gebaseer op die huidige onttrekkingspatroon.

Die algehele impak van klimaatsverandering en ontwikkelingscenario's op Eersteriviervloei kan 'n vermindering in beskikbare water van tussen 2% en 18% in die toekoms meebring. Daarom stel hierdie navorsing voor dat die verhoging van die kapasiteit van bestaande plaasdamme en die bevordering van water aanvraag bestuurs-aktiwiteitedaartoe sal kan bydra om die potensiële impak van klimaatsverandering en ontwikkelingscenario's op die Eersterivier te beberk.

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List of Abbreviations and Acronyms

AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
CCAM	Conformal-Cubic Atmospheric Model
CSAG	Climate Systems Analysis Group
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CMA	Catchment Management Agency
CMIP5	Coupled Model Intercomparison Project Phase 5
DEA	Department of Environmental Affairs
DEM	Digital Elevation Model
DWA	Department of Water Affairs (2009 – 2014)
DWAF	Department of Water Affairs and Forestry (up to 2009)
DWS	Department of Water and Sanitation (2014 to date)
FAR	First Assessment Report
GCM	General Circulation / Climate Model
Ha	Hectare
IAP	Invasive Alien Plant
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
Km^2	Square Kilometre
LiDAR	Light Detection and Ranging
LAM	Limited Area Model
LTAS	Long-Term Adaptation Scenarios
LULC	Land Use and Land Cover
m	Meter

MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
mcm	Million cubic meters
Ml/a	Million litres per annum
Ml/day	Million liters per day
mm/a	Millimeter per annum
Mm^3/a	Million cubic metres per annum
NASA	National Aeronautics and Space Administration
NGA	National Geospatial-Intelligence Agency
NOAA	National Oceanic and Atmospheric Administration
OECD	Organisation for Economic Co-operation and Development
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SANLC	South African National Land Cover
SAR	Second Assessment Report
SAWS	South Africa Weather Services
SPATSIM	SPAtial and Time Series Information Modelling
SRES	Special Report on Emission Scenarios
SRTM	Shuttle Radar Topography Mission
TAR	Third Assessment Report
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
W/m^2	Watt per square metre
WCSA	Western Cape System Analysis
WC/WDM	Water Conservation and Water Demand Management
WCWSS	Western Cape Water Supply System

WCWS-RSS	Western Cape Water Supply Reconciliation Strategy Study
WMA	Water Management Area
WMO	World Meteorological Organisation
WRSM	Water Resources Simulation Model
WUA	Water Users Associations

1. Introduction

1.1 Background

Climate change is considered worldwide as a global challenge of the 21st Century based on the observed increase of global warming due to high concentration of greenhouse gases in the atmosphere (Tari *et al*., 2015). This observation was officially accepted at a global level in 1990 through the First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which is a scientific body established by the United Nations to provide guidance on climate change. This report indicated that there is an increasing trend of global warming since the pre-industrial era, which was in the mid-19th Century (IPCC, 1990).

Based on this trend of global warming, the average global temperature is rising, and it is expected that by 2100, the temperature would rise in the range of 1.4 °C to 5.8 °C relative to the pre-industrial era. It is anticipated that the world is going to continue experiencing frequent occurrence of floods, droughts, heatwaves, and acidification of oceans. At the same time, there might be an increase in uncontrolled spreading of diseases and global food insecurity (Hoegh-Guldberg *et al*., 2018). These events are expected to continue causing devastating impacts on environmental and socio-economic development of the world if climate change is not mitigated.

The impacts of climate change in South Africa might well be experienced already, given the lowest rainfall recorded since 1904 in 2015, and in the same year, the recording of the highest temperature of 42 °C in the City of Cape Town. This situation was worsened given the drought that had a slow onset in 2014 and lasted up to 2018. Thus, there was a high chance that the City of Cape Town could run out of water in a day referred to as “Day Zero” (Burls *et al.*, 2019).

Although the City of Cape Town avoided “Day Zero”, the fear of this occurring again is now certain in the minds of most people, especially farmers, who were profoundly affected during this period. The possibility of “Day- Zero” occurring is considered to be most likely because South Africa is regarded as a water-stressed country, with most of the major water catchments experiencing water deficit (Dallas & Rivers-Moore, 2014). Besides, the climate research community has indicated that even if the greenhouse gas emission to the atmosphere is regulated at this time, climate change impacts will still be felt for some years to come (Patz *et al*., 2014).

To this end, the water sector was identified in the Department of Environmental Affairs (DEA) (2013) study as the sector that is due to experience most of the direct impacts of climate change.

This observation agrees with Schulze's (2011) study which reported that the water resources sector in South Africa is most vulnerable to climate change, feeling the fullest brunt of its impact which reverberate to other sectors like agriculture, health and biodiversity, just to mention a few. It is imperative that comprehensive knowledge of the climate change impacts on this sector is established through research and that action is taken to avoid the catastrophic impact that could be potentially experienced by the society at large.

One way of understanding the impacts of climate change on the water sector is through the use of hydrological modelling (Kusangaya, 2017). In this context, several climate change impact studies using hydrological models have been carried out on water resources of the Western Cape Province in South Africa. Some of the studies include research by New (2002) in Langrivier, Bokkerivier, Kleinsanddrif, and Willemnels catchments; Steynor (2004) in Breede catchment; Louw *et al*. (2012) in Berg and Breede Water Management Areas; DEA (2013) in Breede and Berg Water Management Areas (WMAs), and Pengelly *et al*. (2017) in Berg WMA.

In all these studies, only the study by Louw *et al*. (2012) directly modelled the impacts of climate change on the Eerste River, which is one of the main rivers in the Berg WMA. This study used the Agricultural Catchments Research Unit (ACRU) hydrological model and emission scenarios of Special Report on Emission Scenarios (SRES), which were adopted by the IPCC in 2000.

The current research in climate change is driven by emission scenarios called Representative Concentration Pathways (RCPs). The Global Climate Models (GCMs) that are being used in Coupled Model Intercomparison Project-Phase 5 (CMIP5) are using RCPs to determine the change in global climate (Meinshausen *et al*., 2011). The CMIP5 is the latest world climate change programme that coordinates the global modelling of climate change. Since the adoption of RCPs by the climate modelling community, no climate change impact study has been undertaken on the Eerste River based on these RCPs using hydrological modelling.

This Eerste River is significant in the Cape Winelands region as it is the primary source of water supply to Stellenbosch Municipality (Chingombe, 2012). The vineyards that are irrigated by this river cover 16% of the total area under vineyards in South Africa and contribute significantly to the wine industry, which is a leading agro-based industry in terms of exports (South Africa Wine Industry Information and Systems (SAWIS), 2018). Any negative impact on this river due to climate change could be devastating to the socio-economic development of South Africa, which is the eighth highest producer of wine worldwide.

Climate change is not the only factor that could trigger negative impacts on the availability of water in the Eerste River. Stellenbosch Municipality (2017a) and the Department of Water & Sanitation (2014) have projected through water requirement scenarios, that the water demand for municipal and irrigation water use on Eerste River and Western Cape Province respectively, is expected to grow in the future. This growth in water demand is due to the need for socio-economic development and population growth. Despite all the above, no study has established the combined impact of this future water demand and climate change on the Eerste River.

1.2 Problem Statement

The lack of climate change impacts studies on Eerste River based on the RCPs as highlighted in the previous section, generates uncertainty in the planning and development of the socio-economic activities, especially to the farmers and other developmental actors, who depend on this river. In this way, it creates a situation whereby there is a gap in the availability of updated information that can inform on the impacts of climate change on Eerste River based on the current trends in climate research. This notion motivates an endeavour to use the RCPs under the CMIP5 to determine the impact of climate change on the Eerste River. It becomes more direful considering that the water demand for irrigation and municipal water use is expected to increase in the face of climate change. It is anticipated that meeting this future water demand could be a challenging task because the Western Cape, to which Eerste River is located, is a water-stressed province (Pengelly *et al.*, 2017).

It is expected that the results of this research can assist in developing well-informed water resources planning in Eerste River Catchment concerning water availability in the catchment, and future water demand that could arise due to climate change and development scenarios.

1.3 Objectives of the Research

The main objective of this research is to model the impacts of climate change and development scenarios on the Eerste River using hydrological modelling. The specific objectives of the research are as follows:

- To determine the present-day naturalised flows in Eerste River;
- To determine the impacts of future climate change and development scenarios on the available water of the Eerste River; and
- To investigate the influence of the Eerste River flows impacted by climate change on the future irrigation and municipal water demand.

1.4 Assumptions of the Research

This research has adopted the following assumptions:

- Future climate data projected by Global Circulation Models are plausible; and
- Land cover and land use is expected not to vary in the future period relative to the present-day period. This assumption has been adopted in order to determine the sole impact of climate change and development scenarios on the Eerste River without the influence of changing land cover and land use.

1.5 Outline of the Research

This section provides a general overview of the chapters in this research.

Chapter 1 presents the background and objectives of the research. It justifies the need to carry out the modelling of the impacts of climate change and development scenarios on the Eerste River.

Chapter 2 highlights the literature reviewed on the overview of hydrological and climate change modelling, which include background, approaches, types of models and relevant studies that have been conducted on the Eerste River. This chapter also presents the development scenarios regarding water resources for the Eerste River Catchment and then identifies the gaps that exist concerning the determination of impacts of climate change and development scenarios on the Eerste River.

Chapter 3 then presents the description of the study area regarding the climate, geology, water resources, environment and agriculture.

Chapter 4 highlights the methodology that was adopted to identify the impacts of climate change and development scenarios in the study area. It also presents the data that was collected for the research.

Chapter 5 presents the data analysis and the hydrological model set up that was adopted for the research.

Chapter 6 highlights the results of the research. It also discusses the results based on the objectives of the research presented in Chapter 1.

Chapter 7 concludes the research by highlighting the impacts of climate change and development scenarios on the Eerste River, and then Chapter 8 recommends the areas for further research on the Eerste River based on the findings of this research.

2. Literature Review

2.1 Overview of Hydrological Modelling

Hydrological modelling is the mathematical representation of the water distribution between the atmosphere and land interactions (Siad *et al*., 2019; Hughes, 2004). The main inputs into the hydrological model are atmospheric data, which are rainfall, evaporation, and streamflows, and catchment characteristics data, which are topography, soil and land cover (Nkwonta *et al*. 2017). The main components of the hydrological models are the inputs, boundary conditions, governing equations, model process and outputs.

The need for hydrological modelling is necessitated due to the desire to understand the catchment yields and water availability; design of urban sewer, land reclamation drainage system and dam spillways (Sitterson *et al*., 2017; Nguyen, 2016). Hydrological modelling started with the introduction of the rational method in the 1850s, and it gained more popularity with the onset of the computer revolution in the 1960s. The use of computers saw the birth of numerical and stochastic hydrology which are the backbone of hydrological modelling (Singh, 2018).

Since the 1960s, hydrological modellers were able to simulate watersheds, optimisation and operations of reservoirs and to carry out two and three-dimension modelling. The sediment and pollutant transport, macro spatial scale water bodies like lakes, and integration of hydrology with allied sciences like climate change and global warming, remote sensing and geographical information systems were considered.

As of now, different hydrological models have been developed, which sometimes has caused difficulties amongst modellers to choose which model to use in a specific task. Partly this has been exacerbated due to the lack of benchmarks to compare the models because model developers tend to use different approaches in solving the same hydrological problem or challenge (Todini, 2007). This observation was also noted in the Distributed Model Inter-comparison Project in 2012 in which hydrological models were compared with regard to the simulation of the hydrological cycle. The project concluded that the comparison of models is misleading as models differ in so many aspects of modelling the hydrological cycle (Sitterson *et al*., 2017).

To this effect, Solomatine & Wagener (2011) and Pérez-Sánchez *et al.* (2019) argue that choice of the model should depend on how the model represents the physical processes of the specific catchment, the purpose of modelling, known historical use of the model in a region of interest and the level of details of the catchment to be modelled.

2.1.1 Types of the Hydrological Models

There are three types of hydrological models classified based on randomness, spatial representation, and process description (Nguyen, 2016). These models are described below.

Randomness based models

These models are distinguished based on the presence of random variables in the output of the model. There are two groups under this type of model. These groups are classified as deterministic and stochastic models (Nguyen, 2016; Gao *et al*., 2016). The deterministic models do not consider randomness in their outputs while the stochastic models consider the randomness in their output (Farmer & Vogel, 2016).

The concept of randomness emanates from the understanding that in reality, detailed information for the conservation of mass in the catchment can never exist and that natural processes like infiltration and transpiration are non-linear and cannot be accurately put into mathematical equations (Jonsdottir, 2006). Stochastic terms must be introduced to try to mimic these natural processes because nature has randomness or probabilistic behaviour.

In terms of outputs, Rochester (2010) argued that the deterministic model provides the same output result regardless of the number of modelling runs undertaken for the determined model setup, while the stochastic model has different outputs for every model run due to the inclusion of probability in the model. Farmer & Vogel (2016) observed that designers and managers, especially those dealing with operational hydrology, prefer the use of the deterministic model because it generates the same repeated output compared to the stochastic model which has non-repeated or different output. Rochester (2010) argued that despite the widespread use of the deterministic model over the stochastic models, the stochastic approach is still being advanced in research and practice with the use of deterministic models based on stochastically driven data.

Spatial representation based models

Spatial representation based models deal with the landscape distribution of the catchments. These models are classified as lumped, semi-distributed and distributed (Dwarakish, 2015). The lumped model considers the whole catchment as a single homogeneous unit such that the parameters used in the simulation represent average spatial characteristics of the catchment (Sitterson *et al*., 2017). The catchment runoff is then modelled at the outlet of the catchment and not within specific areas of the catchment. In this way, the computational time of the model is short. However, these models experience loss of spatial resolution such that they are not suitable for large areas.

On the other hand, the semi-distributed model simulates the catchment at hydrological response units commonly denoted as HRUs or sub-basins level within the catchment. The runoff modelled at the end of each sub-basin is then consolidated to represent the runoff of the catchment. In this regard, these models consider spatial variability such that they can have input data which is different within the catchment but homogenous within the sub-basin. The use of these models depends on the input data being lumped in a sub-basin but distributed within the main catchment. They require more catchment details and computational time compared to lumped models.

As for the distributed models, the catchment is portioned into grids or cells and simulation is done at the grid or cell level. The outputs from the grids are merged into one output to get the complete overview of the catchment. This type of the hydrological model is complex as it considers the heterogeneity of inputs and parameters but has a better representation of the catchment. Therefore, this results in having a more detailed simulation of physical representation of the catchment but at the cost of computational time when compared to the semi-distributed and lumped models. In this respect, distributed models are not used often compared to the other two models.

Process Description based Models

The process description models are defined based on hydrological processes that are used in simulating the catchment. There are three types of these models which are physical, conceptual, and empirical. The conceptual or grey-box models interpret the hydrological processes of catchments based on the interaction of surface water and groundwater storage fluctuations. These models deal with rainfall, runoff, evaporation, and groundwater.

The conceptual models differ in complexity such that more input data like meteorological data and other parameters are required to calibrate the model. Besides, these models are easy to use and calibrate. These models also require limited computation time to simulate a catchment such that they are popular among modellers. The main disadvantage is that the models do not consider spatial variability such that the catchment is not simulated in detail (Sitterson *et al*., 2017).

The empirical or black-box models use the non-linear statistical relationship between rainfall-runoff to simulate runoff in catchments. The lack of consideration of physical characteristics of the catchments and much reliance on data to model the catchments have rendered these models to be called data-driven models (Sarkar & Kumar, 2012). These models use Artificial Neural Network, Fuzzy logic, Genetic Algorithm, SCS-Curve number, and Machine learning to establish the relationship between input and output (Dwarakish, 2015).

These models are used based on experience or observations. They are preferred because of cost-effectiveness, faster computational times, few parameters for calibration, and can be used in areas where physical characteristics information of catchments is unknown like ungauged catchments. The main disadvantage of these models is that it can lead to different conclusions which can infer that some methods are wrong when there are so many ways to arrive at the answer.

As for physically-based or white-box models, these models simulate the catchment using the physically-based equations related to hydrological processes which also considers the spatial variability of land surface like topography, slope and climatic parameters like rainfall and evaporation distribution (Wijesekara *et al*., 2012). These physically based equations are those dealing with water balance, conservation of energy, momentum, and mass, e.g. Boussinesq's, Richards's, St Venant and Darcy (Dwarakish, 2015).

These white-box models are considered to be more realistic because of the connection between model parameters and physical catchment characteristics. In this way, these models can incorporate the spatial and temporal variations of the catchments in the simulation processes. As a result, these models require more time, data and parameters to run the model. One of the commonly used physically-based models is MIKE-SHE.

Some of the hydrological models do have traits of two or more types of the hydrological model based on its configuration. For example, MIKE-SHE hydrological model is described as physically-based distributed, SWAT hydrological model as physically-based semi-distributed, while WASMOD hydrological model as stochastic-conceptual (Sitterson *et al*., 2017; Nguyen, 2016).

2.1.2 Common Data for Hydrological Modelling

Most hydrological models require the use of evaporation, precipitation, observed streamflows, and other catchment characteristics (land use and land cover, topography) as input data to model the catchment or hydrological processes. Rainfall and observed streamflows data are typically collected from the rainfall and hydrological monitoring stations, respectively, and are used in the models without requiring additional processing apart from patching and sorting of the data. As for evaporation, land use and land cover, and topography data, these require processing before being adopted in the hydrological models. The procedure that is used to process these data is described in the next section.

Evaporation

The evaporation data requires most of the times conversion from the observed temperature data before it can be used in the hydrological models. The common equations that are used to convert temperature data to evaporation data are Hamon, Hargreaves and Penman-Monteith.

According to Rao *et al.* (2011), the Hamon Equation is expressed as in Equation 1.

$$E_p = 0.165 * k * N * \left(\frac{216.7 * e_s}{T + 273.3}\right) \quad (1)$$

Where:

E_p = Potential Evaporation in mm per day;

k = Proportionality coefficient equal to 1;

N = Daytime Length in number of hours per 12 hours;

e_s = Saturated vapor pressure in millibars; and

T = Average Daily Temperature in °C.

The Hargraves Equation is expressed as in Equation 2 based on Hargreaves & Allen (2003).

$$E_p = 0.0023 * S_o * (T_{max} - T_{min})^{0.5} * (T_{mean} + 17.8) \quad (2)$$

Where:

E_p = Potential Evaporation in mm per day;

S_o = Water equivalent of Extraterrestrial Radiation in mm per day;

T_{max} = Mean maximum daily temperature in °C;

T_{min} = Mean minimum daily temperature in °C; and

T_{mean} = Mean daily temperature in °C.

Allen *et al*. (1998) developed the Penman-Monteith Equation, presented in Equation 3.

$$E_p = \frac{0.408 * \Delta * (Rn - G) + \gamma * \frac{900}{T + 273} * u2 * (es - ea)}{\Delta + \gamma * (1 + 0.34 * u2)} \quad (3)$$

Where:

E_p = Potential Evaporation in mm per day;

Δ = slope vapour pressure curve in kPa per °C;

T = mean daily air temperature at 2m height in °C;

R_n = Net radiation at the crop surface in MJ m^{-2} per day;

G = Soil heat flux density in MJ m^{-2};

γ = psychrometric constant in kPa per °C;

es = saturation vapor pressure in kPa;

ea = actual vapor pressure in kPa; and

u2 = mean wind speed at 2 m height in m s^{-1}.

The choice of the equation to be used to determine evaporation data for hydrological modelling depends mostly on the available data.

Catchment Topography

The catchment topography data, which include river network, location and geometric properties of the catchments, are commonly obtained from Digital Elevation Models (DEMs) and field mapping (Garbrecht & Martz, 2000). Use of DEM is common in most of the hydrological modelling studies because the process of getting the catchment data from DEM is considered to be faster, provide easy integration of generated data with Geographic Information Systems (GIS), and is less expensive than field mapping. On the other hand, field mapping is regarded as a more accurate method of getting topography data than the use of DEM. However, it is time-consuming and expensive, mainly if used in large catchments (Tarboton, 2002).

There are three types of DEMs based on structure, i.e. Grid or Raster, Triangulated Irregular Network (TIN) and Contour-based. Grid DEMs are commonly used because of high computational efficiency and simplicity in use (Garbrecht & Martz, 2000). The DEMs are typically produced using remote sensing, ground surveys and digitising from topographic maps. Therefore, using remote sensing, the DEMs are created using Photogrammetry, Light Detection and Ranging (LiDAR), and airborne and space-borne Interferometric Synthetic Aperture Radar (InSAR), e.g. Shuttle Radar Topography Mission (SRTM) (Hawker *et al.*, 2018).

DEMs are also categorised based on resolution or grid spacing, e.g. 30 m by 30 m resolution or 10 m by 10 m resolution. The resolution means the X-Y distance that a grid represents on the earth surface. Therefore, the smaller the number of resolution for the grid, the better the earth surface details captured by the DEM. These grids also provide ground elevations which are measured above mean sea level. In this respect, it is possible to determine the catchment landscape using GIS tools based on the DEMs, e.g. using ArcGIS or QGIS computer software. The DEMs are mostly sourced from the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) (Garbrecht & Martz, 2000).

Land Cover and Land Use

The land use and land cover (LULC) data is an important input in hydrological modelling as it indicates the changes on earth surface that might have impacts on the water resources. Tizora *et al.* (2016) define land cover as the biophysical characteristics of the earth surface, and land use as human activities undertaken on the land cover. Therefore, changes in land use contribute to changes in land cover. There has been a growing interest in the hydrological modelling community to understand the impacts of LULC on hydrology, especially on the changes of mean annual runoff and extreme hydrological events like floods (Li *et al*., 2019). The LULC data is commonly in the form of a map or raster images. These maps are generated or produced using satellite imagery (Feng & Bai, 2019). In this regard, the LULC maps are produced by classifying the features on the satellite imagery, e.g. forest, built area. Therefore, the LULC maps usually have a legend that highlights these classes for easy identification of features.

The common satellite imagery that is used to produce LULC maps is Landsat which was developed by USGS. Landsat imagery is commonly used because it is considered to be the only longest continuous satellite imagery data with high spatial resolutions of 30 m (Viana *et al.*, 2019). Of late the use of Sentinel-2 satellite imagery in producing the LULC maps is on the increase because this imagery is considered to be of higher spatial resolution (10 m) than the Landsat satellite imagery (Lima *et al.,* 2019).

The Department of Environmental Affairs of South Africa in 2019, adopted the use of the South African National Land Cover (SANLC) 2018 which has replaced the SANLC 1990 and 2013-14. This SANLC 2018 was developed based on the 20 m resolution Sentinel-2 satellite imagery of 2018 which is considered to have better spatial, spectral and temporal features than the SANLC 1990 and SANLC 2013-14. The SANLC 1990 and SANLC 2013-14 were based on the 30 m resolution Landsat satellite imagery of 1990 and 2013-2014, respectively (DEA, 2019).

In hydrological modelling, LULC maps are analysed using GIS computer programs like ArcGIS or QGIS to determine properties (area, type) of land cover and land use like afforestation, irrigated agriculture just to mention a few. After this data is determined using the GIS computer programs, it is then used in the hydrological models to simulate the hydrological processes of the catchments.

2.1.3 The Procedure of Hydrological Modelling

All hydrological models follow common steps in modelling the catchment processes or hydrological system. Solomatine & Wagener (2011), reported that the first step in undertaking catchment modelling is to understand the catchment or hydrological system to be modelled, to which the modeller then identifies the type of the data to be used in the model. The second step is selecting the suitable hydrological model based on the understanding of the model structure to simulate the hydrological processes of the catchment or historical use of the model in the region of interest. The third step is to calibrate the model by known observed hydrological data to which it can be matched with simulated hydrological data within an acceptable parameter threshold. The fourth step is then to validate the calibrated hydrological data using the portion of observed hydrological data that was not used for calibration of the model.

Once the validation is done, Lohani (2018) highlighted that the fifth step is to carry a sensitivity analysis to identify which parameters are sensitive to arrive at adopted model parameters for modelling. When this is achieved, the last step is then the actual modelling of the catchment or hydrologic system using the calibrated and validated model.

Based on the above information on the procedure of hydrological modelling, the next section presents the calibrations and validations of models.

2.1.4 Calibrations and Validations of Models

Hydrological modelling is a complex process because it deals with data that is non-linear at most of the times (Mengistu *et al*., 2019; Pérez-Sánchez *et al*., 2019). In this regard, the hydrological modellers devised a way to ascertain the correctness of the modelling process by checking that observed data matches the simulated data in the model. This art of adjusting model parameters to match simulated data with observed data is known as calibration (Kumarasamy & Belmont, 2018). The procedure that is employed to verify the performance of simulation or the calibration of the model over the slice of the observed time series that was not used for calibration is called validation of the model (Biondi *et al*., 2012).

The calibration process can be automated or manual or a combination of both (Lohani, 2018). The automated calibration procedure allows the adjustment of parameters by allowing the model to search for optimal parameters using most of the times a predefined set of numerical optimisation criteria (Kan *et al.*, 2017). The common numerical optimisation criteria are Root Mean Square Error (RMSE) and the coefficient of determination (Kumarasamy & Belmont, 2018).

This automated calibration procedure is classified as single-objective or multi-objective depending on the number of criteria used in the calibration of the model. If one criterion is used, it will be classified as single-objective, and if more than one, it will be multi-objective (Kan *et al*., 2017). The results from this type of calibration procedure are generally considered to be objective. However, due to lack of human intervention in the modelling process, the identified set of parameters in the model sometimes can be unrealistic to physical processes in the catchment or hydrological system thereby having unmatched observed and simulated data during validation of the model (Kan *et al*., 2017).

As for the manual calibration procedure, it allows the use of expert judgement or the modeller intuition and understanding of the data and catchment to adjust the model parameters (Kumarasamy & Belmont, 2018). This notion is also echoed by Kavetski (2019) who reported that an experienced expert who knows the catchment of interest and the model, will be able to identify which parameters need to be adjusted to get the intended output from the model.

The study emphasised this point by demonstrating that the parameters that can be adjusted in the model to simulate floods in flood-prone areas will be different from those that will be used to simulate water availability in arid areas. This procedure is called trial and error because different trials must be undertaken to reach the desired output (Kan *et al*., 2017; Lohani, 2018). This procedure is the most widely used and recommended for calibration of models. The only downside of this procedure is its laboriousness and sometimes subjectivity (Kan *et al*., 2017).

The parameter estimation in the model either by automated or manual procedures is a common challenge in the hydrological community (Kan *et al*., 2017). The daunting task for hydrological modellers is to identify model parameters that will match the simulated and observed data without distorting the physical processes of the catchment or hydrological system (Kumarasamy & Belmont, 2018).

Despite this challenge, Solomatine & Wagener (2011) argues that if the calibration of the model has satisfied at least three criteria, then the model should be considered well-calibrated. These three criteria are a) consistency of the model with the catchment processes or hydrological system measurements; b) accuracy and precision of model simulations; and c) consistency of model structure and behaviour with the hydrological reality of catchment processes or hydrological system.

2.1.5 Uncertainty in Hydrological Modelling

The world is full of uncertainty because of the complex interactions of different nature and man-made systems. The uncertainty, which is sometimes defined as not being sure or definite about the knowledge of something, has not spared the modelling of hydrological systems. However, the definition of uncertainty in hydrological modelling is attributed to lack of sureness about the outcome of the model on the actual catchment processes or hydrological system (Solomatine & Wagener, 2011).

Gupta & Nearing (2014) observed that research on uncertainty in hydrological modelling had much emphasis since the 1990s. This period is when the hydrological modellers started shifting interests from the optimisation of models to understanding uncertainty in hydrological modelling. This notion is concurred by Farmer and Vogel (2016), who also noted that there is an increasing interest amongst modellers to address the uncertainty in hydrological modelling.

Rafiei Emam *et al*. (2018), Solomatine & Wagener (2011), Her *et al*. (2019) and Tegegne *et al*. (2019) argued that this uncertainty could be attributed to four factors. These factors are a) lack of understanding of the hydrological systems by the modeller; b) errors in measurements and length of timeseries of input data; c) parameter estimation especially inability to identify the appropriate parameter combination due to equifinality (multiple parameter combinations resulting in acceptable model outputs), and d) model structure due to simplification of the real world hydrological systems in the model. Todini (2007) emphasised that uncertainty of the hydrological modelling can also be extrapolated to end users of the model output, especially inappropriate use of the information from the model.

Kapangaziwiri (2015) noted that uncertainty could be classified into two groups which are stochastic and epistemic. The stochastic uncertainty is the one that is inherited from the randomness of natural systems which is beyond man's control. As for the epistemic uncertainty, this is based on the quality and quantity of data, and the configuration of the model structure to represent the hydrological processes or systems in the model. The epistemic uncertainty can be reduced but not completely solved as no model can represent the actual natural hydrological processes or systems in its totality.

Solomatine & Wagener (2011) argued that addressing the above four factors is still a challenge. This notion then entails that with better modelling skills emanating from the knowledge of the hydrological processes, input data and careful design of the model structure, the uncertainty in the modelling processes can be minimised but not entirely eradicated. This observation aligns with Singh (2018), who also argued that whether the model is simple or complicated, it will be associated with uncertainty.

To quantify this uncertainty, the hydrological modelling community has used probability theory in models, especially probability density function (PDF) and statistical elements, like standard variation or variance, and to some extent fuzzy logic (Solomatine & Wagener, 2011). Despite the effort to quantify the uncertainty in hydrological modelling, Liu & Gupta (2007), proposed three ways to reduce the uncertainty in the models. These are a) use of high quality and informative input data; b) improve the model structure to represent the physical processes in the model, and c) improve techniques for hydrological modelling.

Solomatine and Wagener (2011) argued that although there is much interest in research on uncertainty analysis, this concept has not been fully adopted in the decision-making process of hydrology projects because of misconceptions of uncertainty. Some of the misconceptions are that policymakers cannot understand the uncertainty concept, uncertainty is subjective, and uncertainty does not matter in final decisions of hydrology projects because there is already randomness in hydrological processes. In this regard, there is still a long way to go in bridging the research findings on uncertainty analysis to final decision-makers.

2.1.6 Common Models in Hydrological Modelling

Many models are being used in the hydrological modelling community across the world. Addor & Melsen (2019) argued that the selection of the models is mainly based on familiarity of the modeller with the model and region where the study is taking place. This is sometimes done at the expense of better models regarding the research topic and available data of interest. In this way, it results in having certain models being used more often than the others.

Therefore, this section highlights the synopsis of the common models that are used in the hydrological modelling community. The hydrological models presented in this section are based on the literature reviewed in the process of identifying the model to be used in this research. These models are not exhaustive of all common hydrological models. The models have been organised in two parts, i.e. those that are common globally and those that are common in South Africa.

Common Hydrological Models at Global Level

This section highlights the hydrological models that are commonly used in the world. It should be noted that studies about common hydrological models are scarce. Addor & Melsen (2019) reported that they might be among the first researchers to have conducted a bibliometric study on common hydrological models. Their study was based on the review of 1529 published hydrological modelling studies from 1991 to 2018, to which seven common models were identified.

These models were Hydrologiska Byråns Vattenbalansavdelning (HBV), Variable Infiltration Capacity model (VIC), TOPography-based hydrologic model (TOPMODEL), the Precipitation Runoff Modelling System (PRMS), Génie Rural model à 4 paramètres Journaliers (GR4J), the mesoscale Hydrological model (mHM), and Sacramento soil moisture accounting model. Other studies have shown that SWAT, MIKE-SHE and WEAP are also among the common internationally used hydrological models (Gassman *et al.*, 2014; Jaber & Shukla, 2012). These models are briefly described below.

Hydrologiska Byråns Vattenbalansavdelning (HBV)

HBV model is a conceptual-deterministic rainfall-runoff model which analyses the hydrological processes of a catchment. The model was developed by Sten Bergström at the Swedish Meteorological and Hydrological Institute (SMHI) in the 1970s as an integrated hydrological modelling system and was designed to accommodate lumped and semi-distributed catchment modelling.

The model is free software that utilises daily data of rainfall and potential evaporation to simulate hydrological processes of a catchment based on a model structure that has three subroutines that deal with interactions of snow, soil moisture and runoff. The model has been used in more than 50 countries with most studies in flood simulation, hydropower, water supply, dam safety, climate change impact studies, and nutrient load estimates undertaken in Nordic countries (Gao *et al.*, 2016).

Variable Infiltration Capacity model (VIC)

Variable Infiltration Capacity model (VIC) is a macroscale grid-based semi-distributed hydrologic model that has been used for water and energy balance studies in the world. It was developed in the early 1990s by Xu Liang at the University of Washington, and its main components include baseflow and runoff generation; water movement in soil, evaporation, transpiration, and cold season processes.

The model requires minimum and maximum daily temperature, precipitation, wind speed, soil texture and land use as input data. The main distinguishing feature of the model is the use of the variable infiltration capacity curve in the separation of precipitation into runoff and infiltration in the simulation of the hydrological processes. In this respect, the model uses the concept that when soil moisture is high, there is less infiltration and more runoff, and when the soil moisture is low, it is vice versa. The model is free software and has been used in many countries for undertaking hydrological modelling assessments and climate change impact studies (Malek *et al.*, 2017).

TOPography-based hydrologic MODEL (TOPMODEL)

TOPMODEL is a semi-distributed physically-based conceptual model developed by Keith J Bevin and Mike J Kirkby in 1979. The model uses the topography and soil transmissivity in determining the runoff in the simulation of the hydrological processes of the catchment. Runoff generation is done by allowing water to flow from saturated areas to unsaturated areas based on topography. This runoff generation procedure is expressed mathematically in the model using the topographic index and exponential Green-Ampt method.

The model is free software and has been used for flood simulations, climate change impact studies, water resources simulations in terms of quantity and quality in different river basins in the world (Jeziorska & Niedzielski, 2018).

Precipitation Runoff Modelling System (PRMS)

PRMS is a deterministic-distributed physically-based model used for modelling hydrological processes based on climate and land use. It was developed in 1983 by USGS, and different versions have been released to date. The model simulates the energy and water balance equations on a daily time step at sub-basin levels called hydrologic-response units (HRUs), which have homogeneous features in terms of land (slope, soil type) and climate (precipitation, temperature) parameters. The total catchment hydrologic output is the summation of the weighted HRUs outputs in the model. The model is free software and has been applied to different uses of rainfall-runoff modelling, decisions support systems, and climate change impact studies (Markstrom *et al.*, 2015).

Génie Rural model à 4 paramètres Journaliers (GR4J)

GR4J is a daily deterministic lumped hydrological model. It was initially developed as GR3J in France but was later on improved to GR4J. The numbers 3 and 4 in GR3J and GR4J, respectively, represent the number of parameters the model uses to simulate the hydrological processes. In this regard, the four parameters that are used in GR4J model are denoted as XI, X2, X3 and X4. XI is production storage capacity or soil moisture accounting parameter in mm; X2 is groundwater contribution parameter or water exchange coefficient in mm/day; X3 is routing storage capacity parameter in mm, and X4 is time peak ordinate of unit hydrograph or unit hydrograph time base/lag parameter in a day. Using these four parameters, the model converts the daily evaporation and precipitation into daily runoff of the catchment.

The model is also free software and has been used in different countries with most of water resources assessment and climate change impact studies undertaken in Europe (Devkota & Khadka, 2015).

The Mesoscale Hydrological Model (mHM)

mHM is a large scale-distributed-grid based conceptual hydrologic model developed by the Department of Hydrosystems at Helmholtz Centre for Environmental Research in Germany. Its design is based on numerical or mathematical functions that have been used in HBV and VIC hydrological models explained above. The model simulates hydrological processes like discharge and flood routing, deep percolation and base flow, subsurface storage and discharge generation, canopy interception, snow accumulation and melting, soil moisture dynamics, infiltration and surface runoff, and evaporation.

The model simulates these hydrological catchment processes using grid cells, which act as hydrological response units or primary modelling units. The model simulates runoff by using daily or hourly precipitation and temperature as input data with consideration to physical catchment characteristics like vegetation and soil properties. The total catchment output is then the combined weighted outputs from the hydrological response units. The model is free software and has been used in different countries in the world, but most studies have been in Europe (Kumar *et al*., 2013).

Sacramento Soil Moisture Accounting (SAC-SMA)

SAC-SMA is a deterministic lumped model that simulates runoff in a catchment. The model was developed by United States National Weather Service mainly for forecasting river flows. The model simulates the runoff by splitting the catchment into two layers which are denoted as upper and lower zones.

The upper and lower zones have tension and free water components which interacts to generate soil moisture using a set of model parameters. The model allows the rainfall first to fill the upper zone through its tension zone, and if the water is in excess, it then fills the free water component. Once the free water component of the upper zone is in excess, the water percolates to the lower zone to which if the zone is saturated, it then forms the surface runoff. It should be noted that the governing equations of the water percolation from the upper to lower zone is non-linear. The model then routes the surface runoff to the outlet of the catchment to determine the total runoff of the catchment. The model has been used for flood forecasting and different water resources simulations in different countries with many studies carried out in the United States of America. It is also free software (Ajami *et al*., 2004).

Soil and Water Assessment Tool (SWAT)

SWAT is a physically-distributed river basin scale model that is used to simulate the hydrological processes of the catchments. It was developed by USDA Agricultural Research Service at Grassland, Soil and Water Research Laboratory, Texas in the USA.

It is a daily model that simulates land management activities in catchment through use of hydrological response units (HRUs). At each HRU, the model uses climate, soil properties and land cover or land use as input data, and then generates the runoff. The model then routes the runoff from one HRU to the other up to the outlet of the catchment. The accumulated runoff at the catchment outlet is then regarded as the catchment runoff. Apart from determining the quantity of water in the catchment, the model has the capability of modelling water quality, sediment yield and agricultural chemical yield.

It has been used in different countries in the world in studies like climate change impact and water resources assessments, with more studies in the USA. It is very popular for hydrological modelling that considers the use of land use and land cover and is free software (Gassman *et al.*, 2014).

MIKE-SHE

MIKE-SHE is a deterministic-physically distributed model used to simulate hydrological processes in a river basin. It was developed by the Danish Hydraulic Institute (DHI), the British Institute of Hydrology, and SOGREAH in 1977 as Système Hydrologique Européen (SHE). The name MIKE-SHE was determined in the 1980s after further improvement by DHI.

The model can simulate water quantity of the catchment like runoff, evaporation, groundwater movement, and water quality like geochemistry, sediment transport aspects of the catchment. The model is designed to simulate hydrological processes in any catchment regardless of the size and can accept GIS-based data as input, e.g. Digital Elevation Models (DEMs). As a physically-based model, it requires many input data and the modeller to have high-level knowledge of hydrological modelling and details of the catchment. The model has been used for river basin planning, flood forecasting, decision support systems for water resources, among others in different countries around the world but with most studies carried out in Europe. It is not free software (Jaber & Shukla, 2012).

Water Evaluation and Planning Model (WEAP)

WEAP model is a lumped physically-based model that can simulate hydrological processes in a catchment. This model was developed by the Stockholm Environment Institute (SEI). It is mainly used for water allocations in the hydrological system such that it uses the principle of water balance in meeting the water demand and supply.

The model has been designed to use nodes and links to conceptualise the water balance in the catchment. These nodes represent a demand or supply zone within the hydrological system, and the links act as water distribution connections between the nodes. The model requires input in the form of climatic data (rainfall, evaporation), demand (domestic, agricultural, hydropower, and environmental), and supply (rivers, dams, groundwater). The model also allows the user to prioritise water demands so that the available water in the hydrological system can satisfy a particular demand first before the others, e.g. satisfy domestic demand before hydropower demand.

The model outputs include the met and unmet demands, distribution of water in the links, and the total available water in the catchment or hydrological system. The model is famous for water resources planning, water quality and ecosystem assessments, hydropower generation, rainfall-runoff analysis, climate change impact studies and reservoir operations. It has been used in different countries in USA, Africa, and Asia. It is a free software for academic research but for commercial activities, a license must be purchased from SEI (Li *et al.*, 2015).

Common Hydrological Models in South Africa

The literature has shown that there are four hydrological models which are commonly used in South Africa. These models are PITMAN, ACRU, SWAT and WEAP (Droogers *et al.*, 2006; Gassman *et al*., 2014). The SWAT and WEAP models have been explained in the preceding sections; hence their descriptions will not be repeated in this section. The PITMAN and ACRU models are explained below.

Pitman

The Pitman model is a conceptual semi-distributed model which simulates hydrological processes of a catchment. It was developed by W.V. Pitman in 1973 at the University of Witwatersrand, South Africa, as a monthly time-step hydrological model. The model is designed to have timeseries of catchment rainfall and area, mean monthly evaporation, and time series of observed or historical stream flows.

It requires water demands, e.g. seasonal monthly irrigation water requirements and monthly time series of water supply abstractions, vegetation features like afforestation and alien vegetation areas, reservoirs capacity, and groundwater properties as input data to simulate the catchment runoff. The model has capabilities to simulate naturalised and unnaturalised streamflows in a catchment.

The simulation of the hydrological processes considers the use of storages linked by mathematical equations to represent the hydrological processes at the catchment level. Thus, the model simulates these hydrological processes by transferring water from one module to the other based on the configuration of the catchment in the model. These modules are runoff (surface and groundwater routing in the catchment), channel reach (distribution of demand and supply in the catchment), reservoir (dam reservoir analysis of the catchment), irrigation block (analysis of the irrigation activities in the catchment) and mine (deals with the mining activities in the catchment).

There are two versions of the Pitman model, which are the Water Resources Simulation Model (WRSM) and SPAtial and Time Series Information Modelling (SPATSIM) model (Glenday, 2019). The WRSM model is the original PITMAN model developed by Pitman with few improvements to the original model by Pitman and Bailey. The SPATSIM model is the improvement of the original Pitman model especially on the groundwater component of the model and inclusion of GIS platform among others by Hughes from the Institute of Water Research at Rhodes University in South Africa.

The Pitman model is extensively used in Southern Africa, especially South Africa and some countries outside Africa for more than 40 years. It has been used in both practical and research studies like climate change impact studies and water resources assessments for both water quantity and quality (Hughes, 2013). This model is a free software which can be downloaded on request from https://waterresourceswr2012.co.za/ for WRSM version, and without request for the SPATSIM version from https:// www. ru. ac. za /iwr/research/software/ (Hughes, 2013; Bailey & Pitman, 2016).

Agricultural Catchments Research Unit (ACRU) model

ACRU model is a distributed physical-based model that simulates the hydrological processes. It is a daily time-step model developed in the 1970s by Schulze of the Agricultural Catchments Research Unit (currently called School of Bioresources Engineering and Environmental Hydrology) at the University of KwaZulu Natal in South Africa. As a distributed model, it simulates the hydrological processes in sub-catchments or sub-basins such that the total output from the model is the weighted consolidated outputs from the sub-basins.

The model requires climatic data like daily rainfall, daily or monthly evaporation; and physical characteristics of the catchments like land use or cover, and soil properties. In this regard, the model was designed to simulate runoff with consideration to the amount of rainfall and the soil moisture deficit of the catchment-based on the land cover or land use by utilising the multi soil-layer moisture budgeting. The model has been commonly used for modelling agro-hydrological related assessments (sediment and crop yields), water resources (reservoir yield analysis, design hydrology), and climate change impact studies in different countries with most studies in Southern Africa and few studies outside of Africa.

The model is free software which can be downloaded from the website of School of Bioresources Engineering and Environmental Hydrology at the University of South Africa. The model has undergone different developments such that the current version in use is called ACRU4 which means the 4th edition or version of the ACRU model (Kusangaya *et al*., 2017).

2.1.7 Hydrological Modelling Studies in the Eerste River Catchment

There have been several studies on hydrological modelling of the Eerste River Catchment, especially in the modelling of the water resource availability and water quality assessments. Eerste River is an important river in Western Cape, particularly to the Stellenbosch Town regarding municipal and irrigation water use. More information on the Eerste River is in Chapter 3. The hydrological studies that were undertaken in Eerste River Catchment are described in the next section in chronological order of occurrence.

The 1981 Study

The first study to use hydrological modelling for water resources assessments in South Africa was denoted as “The 1981 Study”. This study was commissioned by the Water Resources Commission and used the PITMAN model that was developed in the 1970s by Pitman at the University of Witwatersrand, South Africa. Before this study, two water resources assessment studies had already been undertaken denoted as “The 1952 study” and “The 1969 study” in 1952 and 1969, respectively, but not with the use of the hydrological model (Pitman, 2011).

The 1981 study was the first study to determine the naturalised flows in the quaternary catchments of South Africa with consideration of land use activities, e.g. irrigation, afforestation. The study was done at the quaternary catchment level using a coarse scale of 1:500,000 and covered the 1920-1976 period. The naturalised flows that were simulated were regarded as generalized because the modelling did not consider the finer details of the catchments.

Surface Water Resources of South Africa study of 1990 (WR90)

The Surface Water Resources of South Africa study of 1990 (WR90) also known as "The 1994" study was conducted in the period 1990-1994. In the 1994 study, the Pitman model was upgraded to be used for personal computers because, at that time, a personal computer was regarded as an essential tool for professional work. This revised version of the Pitman model was called the WRSM90, which meant Water Resources Simulation Model of 1990. The release of the WRSM90 model coincided with the adoption of the revised quaternary catchment areas ranging from 100 km^2 to 1000 km^2 such that this model was designed to simulate catchments at these scales. The WRSM90 model was then able to simulate the impact of historical land use (irrigation, abstractions, water transfers) changes of the catchments on water resources (Pitman, 2011).

The modelling approach that was adopted was first to identify gauging stations within the quaternary catchment that had reliable historical or observed streamflow data, then simulate the catchment with consideration to land use and climatic data. Finally, the observed and simulated streamflow data were compared using mean annual runoff (MAR) and other statistical indices. This hydrological modelling approach provided a platform that saw the simulation of the Eerste River Catchment from 1920 to 1989.

The naturalised mean annual runoff for quaternary catchments of G22F, G22G, and G22H, which comprises the Eerste River Catchment, were then determined (Bailey and Pitman, 2016). The interbasin water transfer of Western Cape Water Supply System (WCWSS) also known as Riviersonderend-Berg government water system that conveys water from the Theewaterskloof Dam to Cape Town City and the Eerste River through the Kleinplaas Dam was not modelled in this study. Therefore, the water contribution from WCWSS to the Eerste River was not considered in the adopted naturalised flows of the Eerste River Catchment.

Western Cape System Analysis (WCSA) Study

The WCSA study was initiated due to recognition that there was a rapid increase of water demand in the City of Cape Town in 1989 by the Department of Water Affairs and Forestry (DWAF) and the City Council of Cape Town. The purpose of the WCSA study was to reconcile the water demand and supply for the whole Western Cape area, which also encompasses the City of Cape Town. This study was implemented by DWAF through Nimham Shand Incorporated Consulting Engineers (NSI) in association with BKS Incorporated between 1993 and 1994. The study focused on the Berg, Palmiet, Steenbras, upper Riviersonderend, Molenaars and Cape Town sub-basins, which comprises the Western Cape Water Supply System.

The Eerste River Catchment, being a sub-catchment of the Berg Water Management Area, was also studied using the WRSM90 model from 1950 – 1990. The Eerste River flows were modelled and compared at the gauging stations within the catchment. These gauging stations were G2H008, G2H005, G2H020, and G2H015 (DWAF, 2008a).

It was noted in that study that there was another gauging station 500 m downstream of G2H008 station, denoted as G2H037, which was not used in the study because by this time it had just been opened. It was also observed that the interbasin water transfer from WCWSS to Eerste River was also not considered in the modelling of the Eerste River. The study also recommended the Eerste River Diversion project as one way of supplying water to the City of Cape Town. The proposed aim of this project was to construct an off-channel dam which will be fed by the Eerste River. This dam will have a pipeline that will be conveying water to Faure Water Treatment Works which currently supplies treated water to the City of Cape Town (Van Zyl, 1998). However, this project is yet to be implemented.

Water Resources of South Africa Study of 2005 (WR2005)

The WR2005 study was a 5-year study for water resources of South Africa that was conducted by the Water Research Commission from 2004. This study preceded the WR90 study and is sometimes referred to as “the 2008 study” (Pitman, 2011). The need for this study arose because there was a need to update the WR90 data to reflect the changes that had occurred in the 1990s, especially the drought conditions that were recorded since the 1920s, and the availability of water resources due to changed legislation of prioritising basic human needs and ecological water requirements. Besides, the WRSM90 model had been revised and updated with new features resulting in a revised version of the Pitman model called WRSM2000 in 2002.

Of most importance was the need to prepare water resources information that could assist the Catchment Management Agencies (CMAs). The CMAs are the basic unit organisation for coordination of holistic water resources management and planning at catchment level in South Africa (Middleton & Bailey, 2011). The new features in the WRSM2000 model that necessitated the modelling of water resources for South Africa, were the introduction of surface and groundwater interactions using SAMI and HUGHES methodologies and improved modelling of the impact of irrigation, afforestation, mining, and wetlands on water resources (Pitman, 2011).

The Eerste River was modelled using the WRSM2000 model from 1920 to 2004 in its quaternary catchments. This modelling activity resulted in the determination of naturalised MAR in G22F, G22G and G22H quarternary catchments (Bailey and Pitman, 2016). As observed with the WR90 study, the contribution of interbasin water transfer of WCWSS to Eerste was again not considered in the WR2005 study.

Berg Water Availability Assessment Study (Berg WAAS)

The Berg WAAS project was one of the outputs of the WCSA study. It was initiated as the Skuifraam Dam Project but was later on changed to Berg River Project which comprised the Berg River Dam and other supplement schemes. The aim of this project was following the need that necessitated the WSCA project in 1989, which was to supplement the water supply to the City of Cape Town considering the increase of water demand in the city. In addition to this goal, the BERG WAAS project was to augment the Western Cape Water Supply System as an additional water resource for urban and agricultural water use in Western Cape Province (Mills & Malan, 2008).

The Eerste River was modelled using WRSM2000 model, which was the updated version of WRSM90 model that was used in the WCSA study. The modelling was done for the period 1950 to 2004 by Ninham Shand (Pty) Ltd in association with Umvoto Africa (Pty) Ltd under the supervision of DWAF with reference to the observed flows at G2H037, G2H005, G2H020, and G2H015 gauging stations (DWAF, 2008a). During the modelling of Eerste River under this study, some issues were noted on the modelling of the river.

One of the issues was that the updated Mean Annual Precipitations (MAPs) that were used in the WCSA study were different from the MAPs that were determined during this study. For example, in the area upstream of Kleinplaas Dam, the MAP was determined to be 2293 mm instead of 1900 mm used in the WCSA study. It was noted that using the MAP of 2293 mm resulted in difficulty to determine the model parameters that could fit the simulated MAR to observed MAR of the Eerste River at G2H037 gauging station within the accepted guidelines. This study ended up adopting the MAP of 1900 mm that was used during the WCSA study.

The other issue was that this study used the G2H037 gauging station instead of the G2H008 gauging station that was adopted in the WCSA study because by this time the G2H008 gauging station was closed by DWAF. Another issue was that although WRSM2000 model was upgraded with the SAMI methodology to model the groundwater flows under the WR2005 study, this study did not adopt the use of this methodology in modelling the Eerste River.

It was established during this study that the SAMI methodology was not determining the correct groundwater flows of the Eerste River Catchment. In this way, groundwater water was then modelled based on the observed aquifers data to which monthly timeseries were determined as input in the WRSM2000 (DWAF, 2008a). The last issue was that there was no reliable updated streamflow data for G2H015 gauging station, which led to the adoption of the same streamflow data used during the WCSA study (DWAF, 2007a).

Surface Water Resources of South Africa 2012 (WR2012) study

The WR2012 study was launched in 2012 by the Water Resources Commission to update the water resources information of South Africa from the WR2005 study, and to make the information publicly accessible through the website. The study was undertaken for four years starting from 2012 to 2016 (Bailey and Pitman, 2016).

The water resources of South Africa were modelled from 1920 to 2010 using the revised WRSM2000 model. The revised WRSM model included the enhancement of the SAMI groundwater methodology which was previously considered as having challenges in modelling the actual groundwater in catchments by different water experts including those undertaking the Berg WAAS study as explained above. The study also provided updated information of land and water use (water abstractions, return flows, irrigation, alien vegetation and afforestation), rainfall, observed and naturalised streamflows, and water quality for all quaternary catchments in South Africa. The Daily WRSM 2000 model was also developed to undertake daily time-step simulations of water resources. The above information was made public at WR2012 study website through https://waterresourceswr2012.co.za/ (Bailey and Pitman, 2016).

The WR2012 study also modelled Eerste River although it did not consider the interbasin water transfer from WCWSS to Eerste River through Kleinplaas Dam and G2H015 gauging station similarly to the Berg WAAS study. The main difference between WR2012 study and the Berg WAAS study was that the former configured pine to be part of Afforestation while the latter as part of Alien vegetation in the WRSM2000 model.

2.2 Climate Change Modelling

2.2.1 Background of Climate Change

Climate is generally defined as the average weather for a specific place. This means a place that experiences rainfall in summer or winter seasons at specific months of the year is said to experience summer rainfall or winter rainfall as its climate. This climate varies on an annual basis with regard to the average or mean of its climate parameter. For example, the magnitude of the highest monthly temperature can be above or below the mean monthly highest temperature from one year to another year for a particular place. This phenomenon is referred to as climate variability.

The change of this long-term mean over a long period, usually, 30 years, is referred to as climate change. These patterns of climate, whether by variability or long-term change, is caused by the interactions of atmospheric and oceanic circulations which are influenced by solar radiation to the earth surfaces (Ramamsy & Baas, 2007). This solar energy radiates back to the atmosphere and is later lost to outer space. Through this process, the solar energy interacts with different matter in the atmosphere to which some of these are greenhouse gases and aerosols. These greenhouse gases, which are mainly carbon dioxide, methane and ozone, trap some of the solar energy to maintain earth atmospheric temperature that necessitates the support of life.

In the mid-1980s the scientific community reported that beyond the natural variability, the anthropogenic activities are causing the greenhouse concentration to be enhanced to a level where the temperature on the earth surface is increasing, resulting in a warmer earth. This situation was exacerbated by the discovery of a hole in the ozone layer and later on the occurrence of a heatwave in 1988 (De Chazournes, 2008).

The United Nations Environment Programme (UNEP) and World Meteorological Organisation (WMO) in 1988 established the Inter-governmental Panel on Climate Change (IPCC) as a scientific body on climate change through the UN General assembly Resolution 43/53 of 6 December 1988. The IPCC objectives were to undertake detailed assessments of scientific knowledge on climate change, develop response strategies, and review the economic and environmental impact of climate change (IPCC, n.d.).

The IPCC regularly convenes scientific conferences of experts that update the policymakers on the latest research findings or knowledge related to climate change. This is mainly done based on recommendations from three Working Groups denoted as Working Group I, Working Group II and Working Group III.

Working Group I is mandated to assess the scientific knowledge or basis of climate change from the scientific community. At the same time, Working Group II deals with susceptibility of socio-economic endeavours and nature to climate change. As for Working Group III, it is concerned with response strategies to climate change impacts through the advocacy of mitigation and adaptation measures (IPCC, n.d.; Zillman *et al*., 2001). IPCC does not conduct its own climate change research.

The IPCC has released 6 Assessment Reports called First Assessment Report (FAR), Second Assessment Report (SAR), Third Assessment Report (TAR), Fourth Assessment Report (AR4), and Firth Assessment Report (AR5) in the following years 1990, 1995, 2001, 2007 and 2014, respectively. The Sixth Assessment Report (AR6) is being formulated at present, expected to be released in 2022. In addition to the assessment reports, the IPCC also produces Special and Methodology Reports (IPCC, n.d.).

The main highlights of the reports are that the FAR emphasised that climate change was a global challenge requiring international cooperation. The report recommended the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) as a treaty that member states should adhere to reduce global warming. The SAR then built on the FAR by proposing the Kyoto protocol, which guided the lowering of greenhouse gases emissions by the international community. The TAR focused more on advocacy on the adaptation to the impact of climate change.

The AR4 continued from the TAR by recommending through the Paris Agreement (an agreement that was made in Paris, France by the international community) that global warming should be limited to a maximum of 2 °C increase above pre-industrial levels to avoid the exacerbation of climate change due to anthropogenic activities (Gao *et al*., 2017). The AR5 then provided scientific input into the Paris Agreement on how global warming should be limited to the target of 2 °C by the international community. It is expected that the AR6 will continue the implementation of the Paris Agreement (IPCC, n.d.).

2.2.2 Climate Change Emission Scenarios

The climate change emission scenarios are perspectives or storylines on how climate change will unfold in the future regarding socio-economic development, demography, and technological advancement based on the atmospheric concentration of greenhouse gases and aerosols. The emission scenarios are highly uncertain due to the complex nature of the climate and its driving forces. No probability can be attached to the occurrence of the emission scenarios (Nakićenović *et al*., 2000).

These emission scenarios do undergo critical review by the scientific community before the IPCC adopts them. These scenarios are regarded as the tools that can assist in determining the impact of climate change on humanity and the environment. The scientific community has been using the IPCC emission scenarios to undertake climate change modelling for climate change impact assessments, and the development of climate change adaptation and mitigation measures.

The first emission scenarios to be advanced by the IPCC were in 1990 to which four scenarios (A to D) were developed (IPCC, 1990). These scenarios projected the atmospheric emission of greenhouse gases like carbon dioxide, methane, carbon monoxide and others from 1990 to 2100. Scenario-A also called "Business as usual" was assumed to promote intensive uses of coal, advance deforestation till tropical forests were exhausted, and considered that production of methane and nitrous oxide from the agricultural sector was out of control.

Scenario-B proposed the reduction of carbon emission and preserving the use of biomass as a source of energy in this century. Scenario-C promoted the use of renewable energy like nuclear and prohibited bio-mass in the second half of the century. Scenario-D was opposite of Scenario-C with renewable energy and reduction of bio-mass use being advocated in the first half of the century. Of these four scenarios, Scenario-A, which was also denoted as SA90 was adopted by the international community and was the driving scenario for climate change impact assessments and other research efforts until 1992.

In 1992 there were new developments relating to assumptions adopted in the SA90 that necessitated the update of this scenario. Six new emission scenarios were developed for the period 1990-2100, which were denoted as IS92a, IS92b, IS92c, IS92d, IS92e and IS92f (Leggett *et al*., 1992). The underlying assumptions in these scenarios were that in IS92a the population and economic growth would be 11.2 billion and 2.3%, respectively, at 2100 and developing countries will make efforts to reduce the emission of greenhouse gases by mid-century.

As for the IS92b, the assumptions were those of IS92a, but with consideration of additional member states of Organisation for Economic Co-operation and Development (OECD) reducing the emissions by mid-century. The IS92c inherited the assumptions that the population and economic growth will be 6.4 billion and 1.2%, respectively, at 2100 with the same countries as in IS92b scenario reducing their emissions by mid-century (Leggett *et al*., 1992).

In the IS92d scenario, it was assumed that greenhouse gas emissions would be reduced globally by stopping deforestation, and that population and economic growth will be 6.4 billion and 2%, respectively, at 2100. As for the IS92e, the assumptions were that economic and population growth would be 3% and 11.3 billion, respectively, at 2100. The IS92e also assumed that the implementation of greenhouse gas emissions measures would increase fossil energy costs. Finally, the IS92f scenario assumed the same emission measures of IS92e but with population and economic growth of 17.6 billion and 2.3%, respectively, at 2100.

Of all six IS92 scenarios by IPCC, the IS92a scenario was mostly used in the climate change impact assessments by the scientific community up to 1996; when new information about climate change had emerged which required that the scenarios be reviewed again (IPCC IS92, 2019). In 1996, new climate change emission scenarios were developed, which were more of a contribution to the Third Assessment Report of IPCC. These scenarios were called the SRES emission scenarios based on the Special Report on Emissions Scenarios that proposed these scenarios to the international community and was accepted by the IPCC Working Group III in 2000 (Nakićenović *et al*., 2000).

These SRES scenarios also assumed that there were no polices for mitigation of the impacts of climate change in the future, similarly to the IS92 scenarios. Initially, four SRES scenarios were proposed denoted as A1, A2, B1 and B2. The A1 Scenario was further sub-divided into A1F1, A1T and A1B scenarios. The splitting of A1 Scenario made the SRES scenarios to be six in total. These SRES scenarios were all describing the future greenhouse gas emissions based on the same basis of the previous scenarios, which were demography, technological and economic development. The A1 scenario was telling a storyline of having new and efficient technologies in term of energy use, exponential economic development, and an increase in global population till the mid-century, which later decreases. The three scenarios which emerged out of A1 were disaggregated based on the type of energy source that was driving the technology advancement. A1T and A1F1 Scenarios assumed use of non-fossil and fossil energy, respectively, while A1B Scenario, it was the use of both non-fossil and fossil energies.

As for the A2 scenario, it was assumed that there would be a slow increase in the global population; technological and economic development will be localised, dispersed and slower than other scenarios. In terms of B1 Scenario, it was assumed that there would be rapid economic growth, efficient energy use technologies and the same global population pattern like A1 Scenario. As for B2 Scenario, it was assumed that there would be slow and multiple technologies that maximise the use of energy than B1 and A1 Scenarios with increasing population growth at a decreasing rate than A2 scenario (IPCC, 2001).

The SRES Scenarios have been used in most of existing literature on the modelling of climate change impacts on humanity and nature and were also adopted as input into the Fourth Assessment Report of IPCC in 2007. The new information about climate systems, technological and socio-economic developments, the need to incorporate new ideas into climate change policies, advancement of climate change modelling capabilities by scientists, and environment changes like land use and cover necessitated the development of new scenarios (Moss *et al*., 2010).

The IPCC in 2006 decided to have new emission scenarios. However, this time being originated from the scientific community and not from the IPCC terms of reference like it was done in the development of previous IPCC emission scenarios. The scientific community identified the emission scenarios based on the pathways of radiative forcing trajectory. These emission scenarios were called Representative Concentration Pathways (RCPs) and were adopted in the Firth Assessment Report (AR5) of IPCC in 2014. The term “Representative” was used because it meant these scenarios represent several scenarios that have the same radiative concentration and emission. The term “concentration pathways” meant the trajectory that the concentration of greenhouses gases would take to reach a desirable outcome (Moss *et al*., 2008). Four RCPs were developed by the scientific community based on the radiative concentration denoted as RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5.

The RCP 2.6 is the emission scenario where radiative concentration reaches 2.6 W/m^2 (Watt per square metre) in 2040 and reduces towards the year 2100 relative to pre-industrial period and represent the most conservative mitigation scenario. The RCP 2.6 is also regarded as the pathway that targets to limit the global warming below the 2°C of the pre-industrial temperatures and was promoted to the scientific community by PBL-Netherlands Environmental Assessment Agency (Misgana, 2018). The RCP 4.5 and RCP 6 represent the intermediate scenarios of radiative concentration, which are 4.5 W/m^2 and 6 W/m^2, respectively, before the year 2100. RCP 4.5 and RCP 6 are considered to be similar to B1 and B2 SRES scenarios, respectively, and were advanced by Pacific Northwest National Laboratory in the USA and National Institute for Environmental Studies in Japan respectively (Misgana, 2018; Moss *et al*.,2010).

As for the RCP 8.5, it represents the worst scenario whereby the solar radiative concentration reaches up to 8.5 W/m^2 in 2100 due to greenhouse concentration and is usually compared to A2 and A1F1 SRES scenarios (Wayne, 2013). This scenario was promoted to the scientific community by the International Institute for Applied System Analysis in Austria. As of now, these four RCPs are the ones that the research community is using in conducting climate change impact studies and other climate-related research.

2.2.3 Climate Models

Global climate is modelled with the use of the Global Circulation Models or Global Climate Models (GCMs). The GCMs represent the physical processes that occur on land, ocean, and atmosphere regarding dynamic climate systems using the differential equations based on laws of physics like conservation of mass, energy, and momentum; and sometimes include chemistry. The GCMs use the principles of weather forecasting and are used in projecting long-term future climates (Mechoso & Arakawa, 2015).

The GCMs determine the future climate based on the trends, not actual events, that will occur. In this way, the GCM might project that a particular area will have high precipitation in summer without being specific of the dates that precipitation will occur. There are two types of GCMs which are called Ocean Global Circulation Model (OGCM) and Atmosphere Global Circulation Model (AGCM). The AGCM simulate the atmospheric circulations with use of sea surface temperatures while the OGCM simulate the oceans and land surface circulations. The OGCM is sometimes coupled to AGCM to form the coupled Atmosphere-Ocean Global Circulation Model (AOGCM), which can simulate the surface, ocean, and atmospheric circulations (Samadi & Tajiki, 2010). Therefore, AOGCMs are called state of the art GCMs.

AOGCM represent the earth in a 3-dimensional grid system that has a series of layers in both vertical and horizontal directions, to which the atmospheric and oceanic circulations of climate variables are realistically represented by the AOGCM at a global level (Rydgren, 2007). The scientific community commonly use the AOGCMs because of the reliable capability in projecting future climate (IPCC, 2007). Climate modelling is done by forcing these AOGCMs with emission scenarios adopted by the IPCC like the SRES or RCPs to generate plausible future climate variables like temperature and precipitation. In most cases, the AOGCMs are commonly referred to as GCMs.

Some of the common GCMs are MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-M, CanESM2, CCSM4, CESM1(BGC), CMCC-CM, CMCC-CMS, CNRM-CM5, CSIRO-Mk3-6-0, EC-EARTH, FGOALS-g2, ACCESS1-0, ACCESS1-3, bcc-csm1-1-m, bcc-csm1-1, BNU-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-R, HadGEM2-CC, HadGEM2-ES, INMCM4.0, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, NCAR PCM, ECHAM4, CCSR/NIES, CGCM1, CGCM2, GFDL-R30, CSIROMk2b, HadCM2, HadCM3,GFDL-R15 and CGCM3 (Samadi & Tajiki, 2010; Khan *et al.*, 2018).

The WMO under the working group of World Climate Research programmes established the Coupled Model Intercomparison Project (CMIP) in the mid-1990s based on the diversity of the GCMs as a way to coordinate the climate modelling community through sharing, comparing, and analysing the outcomes of the GCMs. Through this platform, standards for climate modelling approaches are discussed for the future development of GCMs and climate modelling. As of now, 5 phases of the CMIP have been implemented denoted as CMIP1, CMIP2, CMIP3, CMIP4 and CMIP5. The 6th phase denoted as CMIP6 started in 2013 and is expected to end in 2020 (Eyring et al., 2016), and will inform the 6th IPCC Assessment Report.

2.2.4 Downscaling of Global Climate Model Outputs

The GCMs simulate the climate scenarios using a grid system. However, each grid covers hundreds of kilometres to represent part of the earth surface. The GCMs operate at a large scale which has a coarse resolution. The term coarse resolution means that the length of each grid-scale is more than 80 km or sometimes 100 km (Hannah, 2015). At this resolution, local features like mountains ranges or convective rainfall cannot be captured by the GCM.

The GCM also tends to have homogenous output from the grid. For example, each grid cell can only have one value of precipitation or temperature, which is assigned to the whole area of the earth surface that is being represented by that grid cell. These climate variables are simulated at a larger temporal scale, i.e. monthly or annually, which means the local variability of these climate variables at lower temporal scales, e.g. daily changes are not considered by the GCM. Therefore, the GCMs are good at simulating climate scenarios at a higher time scale and global level (Trzaska & Schnarr, 2014).

The climate variables simulated by the GCM are required at the local scale to carry out climate change impact study or assessment of hydrological processes. Such information cannot be directly deduced from the outputs of the GCM. There is a need to convert the climate variables from the global scale to the local scale. The procedure that is used for this conversion of climate variables is known as downscaling technique (Samadi &Tajiki, 2010). There are two methods of downscaling the GCM outputs to local scale. These are called Dynamical and Statistical Downscaling.

Dynamical downscaling uses the Regional Climate Model (RCM), which is nested in the GCM to downscale the GCM output to the local level. This RCM operates like a GCM in such a way that it uses the grid cell system but at a finer scale of up to 10 km. In this regard, the RCM is also known as the Limited Area Model (LAM) because the model simulates future climate at a small scale (limited area) (Teutschbein & Seibert, 2010).

The RCM can capture local features like mountains, land use or cover, rivers, or lakes, and use the output or boundary conditions from the GCM to determine the climate variables at a fine scale. In this way, temperature variation with altitude and orographic rainfall can be simulated.

The outputs from dynamical downscaling are still subject to the quality or biases that are inherited from the GCM. Bias correction is required to remove the inherited biases from the GCM outputs. Downscaling using this technique requires supercomputers with large data storage because the RCMs being physically based models use lots of data and takes much time to model climate, e.g. more than a month. This method can be used to downscale the GCM outputs, even in areas that do not have historical climate variables data (Rydgren, 2007).

In terms of Statistical Downscaling method, the GCMs outputs are downscaled using an empirical statistical relationship between large-scale and local-scale climate variables. These local-scale historical variables are called “predictands”, while the large-scale variables are called “predictors”. The downscaling procedure is determined by establishing the relationship between the predictands and predictors and applying this relationship to the GCM outputs to establish the climate variables at the local scale.

There are three methods which are used to statistically downscale the GCMs outputs. These methods are Perfect Prognosis (PP), Model Output Statistics (MOS), and Weather Generator (Evans *et al*., 2012). Hannah (2015) highlighted that the predictand and predictor need not be of the same climate variables. For example, the predictand can be atmospheric pressure, while precipitation can be a predictor. The primary assumption in this method is that the existing statistical relationship will remain valid even in the future climate simulations, a condition called stationarity. The method requires observed historical data to downscale the GCM outputs.

Statistical downscaling is regarded as a reliable method, especially in situations whereby GCM outputs are to be downscaled to a point or an area at a local scale; when there is no information on physical processes of climate variables (Rydgren, 2007). Most scientists who carry out climate change impact studies prefer the use of Statistical Downscaling over the Dynamical Downscaling to downscale the GCM outputs to the local scale because of the time factor and the availability of supercomputers (Forsythe *et al*., 2019).

2.2.5 Uncertainty of Climate Change Modelling

The use of GCMs as tools for climate change modelling is subject to uncertainty as it deals with complex climate systems (Qian *et al*., 2016). GCMs tends to simulate the same climate variables with different magnitudes or sometimes direction of change. For example, some GCMs might indicate that precipitation will increase in the future at a local place while others might show otherwise. This difference in the projection of future climate by GCMs, in this case, precipitation generally results in the uncertainty of the direction of the future climate. In this way, there will always be uncertainty associated with climate change modelling (Katz *et al*., 2013).

The uncertainty in climate modelling arises due to imperfect representation of the climate processes in the GCMs and the quantification of the greenhouse gases in the emission scenarios that force the GCMs. Difficulties in determining the initial conditions of climate variables before starting the simulation process and challenges to represent climate variability for a long term period also contribute to uncertainty (Trzaska & Schnarr, 2014). Idso & Singer (2009) reported that it is difficult to simulate the actual processes of earth's radiative energy balance, especially when it comes to high cirrus cloud ability to radiate the solar radiation. Parameterisation of the GCM to determine the future cloud formation is still also a tall order. Evans *et al*. (2012) further attributed the assumptions that are used in downscaling techniques of the GCMs outputs to be exacerbating the uncertainty in climate change modelling. This source of uncertainty is further compounded by the use of the emission scenarios in GCM, which are considered to have inherited uncertainty in their formulation.

Hawkins (2013) also emphasised that according to the CMIP5 conclusions, it has been noted that the main uncertainties associated with climate modelling are future emissions, internal climate variability and inter-model differences. Of these three uncertainties, internal variability and estimates of future emission are the uncertainties that will affect the climate modelling community for the next years to come.

Trzaska & Schnarr (2014) argued that the presence of uncertainties in climate change modelling does not mean the outputs are false nor that the uncertainties cannot be quantified. One of the ways used to quantify the uncertainties in climate modelling is the application of statistical methods like the square root of error variance which determine the uncertainty of the model outputs in space and time (Woldemeskel *et al*., 2016). The other way is the use of multi-model ensemble which determine the direction of future climate by the median or mean value of the models' output (Qian *et al*., 2016).

The IPCC developed a guidance note on assessing the uncertainty of the GCMs outputs based on the scale of confidence levels. This guidance note is presented in Table 1 based on outputs of 10 GCMs (Schulze, 2011). Table 1 highlights that if at least 9 out of 10 GCMs outputs have the same direction of change, e.g. increase in precipitation, then there is very high confidence that precipitation will increase in the future.

Table 1: Scale of Confidence in GCMs Uncertainty

Confidence Terminology	Degree of Confidence
Very high confidence	At least 9 out of 10
High confidence	About 8 out of 10
Medium confidence	About 5 out of 10
Low confidence	About 2 out of 10
Very low confidence	Less than 1 out of 10

This guidance emanates from the understanding that all models produce plausible expected outputs of the future climate. Choosing one or two GCM outputs among the many GCM outputs to be representative of the future climate would not be the correct way. A multi-GCM change of direction of future climate is promoted as a representative indicator of possible future climate because the uncertainty of the GCMs projections is considered to have been minimised. This change in the direction of the climate variable is determined based on the climate change signal, which is explained in the next section.

2.2.6 Climate Change Signal

Climate change is generally detected with the use of climate variables simulated by the GCMs. The climate change signal is defined as the quantitative measure of climate variables between the baseline scenario and the future scenario determined by the GCMs for the same location (Ivanov *et al.*, 2018). Climate change signal is commonly determined for temperature and precipitation, although other studies like Fant *et al.* (2016) also used wind speed and solar radiation. This notion agrees to Deng *et al.* (2018) study that reported of late, there is growing attention for climate change impact studies to use wind speed and solar radiation, especially in detecting the vulnerability of renewable energy in the face of climate change.

The climate change signal for temperature and precipitation is commonly determined using change (perturbations) factors, also known as delta factors (Anandhi *et al.*, 2011; Hughes *et al.*, 2013). These change factors are additive / difference and multiplicative between the future scenario and baseline scenario for temperature and precipitation, respectively (Ivanov *et al.*, 2018).

Mathematically these change factors are expressed as presented in Equations 4 and 5 for precipitation and temperature, respectively.

$$CCS_{Prec} = GCM\text{-}Future_{Prec} \,/\, GCM\text{-}Baseline_{Prec} \quad (4)$$

$$CCS_{Temp} = GCM\text{-}Future_{Temp} - GCM\text{-}Baseline_{Temp} \quad (5)$$

Where:

CCS_{prec} = Climate Change Signal for precipitation;
$GCM\text{-}Future_{Prec}$ = Mean Precipitation of Future Scenario by GCM;
$GCM\text{-}Baseline_{Prec}$ = Mean Precipitation of Baseline Scenario by GCM;
CCS_{Temp} = Climate Change Signal for Temperature;
$GCM\text{-}Future_{Temp}$ = Mean Temperature of Future Scenario by GCM; and
$GCM\text{-}Baseline_{Temp}$ = Mean Temperature of Baseline Scenario by GCM.

The additive/difference and multiplicative change factors are used for temperature and precipitation, respectively, because it is assumed that GCMs determine plausible absolute changes of temperature and relative change of precipitation (Anandhi *et al.*, 2011). The multiplicative change factor rather than additive/difference change factor is used for precipitation to avoid negative absolute values that could result in cases where the future scenario value is less than the baseline scenario value.

When climate change signal is determined by an ensemble of multiple GCMs, the mean or median of the climate change signals determined by the GCMs is used as representative climate change signal (DEA, 2016b; Schulze, 2011). This approach of using multi-model ensemble to determine the climate change signal is also regarded as one way of instituting confidence in the simulations of climate change in future climates as it removes the uncertainty that is inherited from individual model configuration (Landman *et al.*, 2012).

Climate change signal is transferred to observed temperature and precipitation data using Equations 6 and 7 (Dessu & Melisse, 2012).

$$CI_{Prec} = Observed_{Prec} * CCS_{Prec} \quad (6)$$

$$CI_{Temp} = Observed_{Temp} + CCS_{Temp} \quad (7)$$

Where:

CI_{Prec} = Climate Change induced Precipitation;

Observed $_{Prec}$ = Observed Mean Precipitation;

CCS_{Prec} = Climate Change Signal for Precipitation;

$Observed_{Temp}$ = Observed Mean Temperature;

CI_{Temp} = Climate Change induced Temperature; and

CCS_{Temp} = Climate Change Signal for Temperature.

The climate change-induced temperature and precipitation calculated using Equations 6 and 7, respectively, are then used as inputs in the hydrological model to determine the change in the mean annual runoff with respect to the observed historical data. In other hydrological models that use evaporation instead of temperature, the climate change-induced temperature is converted to evaporation using either Hamon, Hargreaves or Penman-Monteith equations highlighted in Section 2.1.2 (Andersson *et al*., 2006).

In some cases, these equations are modified by assuming that some of the components in the equations will remain constant, especially when the data for other variables in the equation is not available for the impact studies. The Hughes *et al*. (2013) study used a modified Hargreaves Equation to which wind speed and relative humidity were assumed to be constant and only temperature was the variable that was used to determine evaporation of the future and present-day periods. This method was adopted because the temperature was the only available data simulated for the future climate by the GCMs.

This modified Hargreaves Equation is presented in Equation 8.

$$MHC_{jk} = (Tmax_{jk} + TMin_{jk}) / 2 * (Tmax_{jk} - Tmin_{jk})^{0.5} \quad (8)$$

Where:

MHC_{jk} = Temperature Component of Hargreaves Equation for GCM k and Month j for Future or Present-Day Period;

$Tmax_{jk}$ = Mean Monthly Maximum Temperature for GCM k and Month j; and

$Tmin_{jk}$ = Mean Monthly Minimum Temperature for GCM k and Month j.

The climate change signal for evaporation is then determined as the ratio of the MHC_{jk} for future and present-day periods expressed in Equation 9.

$$CCS_{evapo} = MHC_{jk}\ (Future) / MHC_{jk}\ (Present\text{-}day) \quad (9)$$

Where:

CCS_{evapo}	= Climate Change Signal for Evaporation;
MHC_{jk} (Future)	= Temperature Component of Hargreaves Equation for GCM k and Month j for Future period; and
MHC_{jk} (Present-day)	= Temperature Component of Hargreaves Equation for GCM k and Month j for Present-day period.

The climate change signal for evaporation determined by Equation 9 is the change factor that is then used to transfer the climate change signal to the observed evaporation data similar to precipitation, using Equation 6. This climate change impacted evaporation data is used as the input in the hydrological model to determine the change in the mean annual runoff between the present-day and future periods based on climate change.

2.2.7 Bias Correction in Climate change

Global climate systems are very complex such that exact representation of these systems in the GCM is a challenge. The GCM tend to simulate climate change at a higher resolution which results in the introduction of biases in GCM outputs. These biases emanate from the model configuration that overshadows the conceptualisation of the local-scale climate characteristics, e.g. occurrence of orographic rainfall (Teutschbein & Seibert, 2010). However, GCMs are the only scientific tools that are currently available to simulate climate change.

Climate model bias correction is defined as the procedure of removing systematic differences between the simulated and observed climate variables of the same period and place (Maraun *et al.*, 2017). Thus, bias correction is done by comparing the statistics of climate variables of baseline or control scenario with historical or observed time series. The biases once identified, are then used to correct the climate variables of the future scenarios (Teutschbein & Seibert, 2010). This is done with the assumption that the same pattern of biases identified between the baseline scenario and observed time series exists in the future scenarios. In other words, biases are time-invariant between the baseline and future scenarios.

Johnson & Sharma (2015) recommends that bias correction should be done first before the GCMs outputs are applied in the climate change impact studies. There are so many methods that exist for bias correction. The common methods in the literature are Delta Change and Quantile Mapping (Eekhout & Vente, 2018).

There are still debates in the use of bias correction to the GCM outputs. Some researchers have argued that bias correction distorts the climate change signal that has been simulated (Op de Hipt *et al*., 2018). Others have argued that biases might be originating from outside the sphere of influence of GCMs, like difficulties to conceptualise the occurrences of El Niño and rain drizzles in GCMs which bias correction method cannot resolve. Some also argue that bias correction tends to hide the truth of the deficiencies of GCM to simulate the climate of the baseline or present-day period from end-users of the bias-corrected outputs (Ehret *et al*., 2012).

Maraun *et al*. (2017) argued that bias correction should still be promoted only if the physical climate systems processes are well understood and captured correctly in the GCM, and local climate variability in time and space are resolved by the GCM. If these factors are not considered in the projection of future climates using GCMs, then the bias-corrected outputs from GCMs should be handled with care.

2.2.8 Approaches to Climate Change Impact Studies

Climate change impact studies are usually carried out using two approaches. These approaches are Top-Down and Bottom-Up (Conway *et al*., 2019). The Top-Down approach is implemented starting with the identification of emission scenarios and then the selection of GCMs to run the emission scenarios. This step is followed by downscaling of GCMs outputs to a specific local area and then running the impact model using the GCMs outputs to determine the impact of climate change on the sector of interest in a specific local area, e.g. water resources in Stellenbosch.

This approach promotes climate change on the sector of interest as a cause of vulnerability of the sector without critically analysing other non-climate change factors that might affect the sector. In other words, climate science drives the adaptation plans of the sectors (Alodah *et al*., 2019).

As for the Bottom-Up approach, the first step is to understand the existing vulnerability and pressures on the sector of interest, e.g. water or agriculture, and then identify the influence of climate on the sector, e.g. frequency of occurrences of dry spells. Based on this analysis, the GCMs outputs are then used to validate or verify if climate change is indeed the cause of the vulnerability of the sector or not. This approach tends to suggest that climate change and even non-climate change factors drive adaptation of the vulnerability of the sector of interest (Conway *et al*., 2019).

The Top-Down approach is preferred over the Bottom-Up approach, especially in carrying out climate change impact studies because it is not intensive and has been widely used in the climate research community. Top-Down and Bottom-Up approaches are referred to as "the first generation" and "the second generation" approaches, respectively because the former approach was first to be adopted for climate change impact assessment rather than the latter approach (Approaches to Climate Change Impact Assessment, 2016).

Both approaches have advantages and disadvantages. The choice of the approach to be used depends on the objectives of the impact assessment to be undertaken, e.g. assessment of community adaptation to the vulnerability of climate in the water sector (Bottom – Up) while analysis of water sector response to climate change impacts (Top-Down). Conway *et al*. (2019) advocated that integrating the results from both approaches is the best approach for climate change impact assessment.

In all the above approaches, the impact of climate change on water resources is determined by comparing the mean annual runoff determined using the hydrological model between the future and the present-day periods. The mean annual runoff for future periods is determined using climate change-induced data in the hydrological model. As for the mean annual runoff for the present-day period, the observed climate data for the baseline period is used in the hydrological model.

In this respect, Mengitsu and Sorteberg (2012) indicated that the impact of climate change on water resources is determined as expressed in Equation 10.

$$\Delta Q = \frac{Q_{future} - Q_{observed}}{Q_{observed}} * 100 \tag{10}$$

Where:

ΔQ = Change in Mean Annual Runoff in percentage (%);

Q_{future} = Mean Annual Runoff in Future periods in Mm^3; and

$Q_{Observed}$ = Mean Annual Runoff in Present-Day period in Mm^3.

A positive change in mean annual runoff in Equation 10 indicates an increase in the runoff while the negative change is conversely correct.

2.2.9 Climate Change Studies in South Africa

This section highlights the climate change studies that have been undertaken in South Africa, especially in Western Cape and the Eerste River Catchment.

South Africa (National Level)

Climate change as a global phenomenon is considered to have affected all countries, including South Africa. South Africa is regarded as one of the countries in the world which is vulnerable to climate change because it is a semi-arid country with an average MAP of 480mm and Mean Annual Evaporation (MAE) of 1790 mm (Cullis *et al*., 2015).

The Government of South Africa has proposed measures for mitigation and adaptation to the effects of climate change through policy instruments like the National Climate Change Response Policy, National Development Plan 2030, and National Climate Change Monitoring and Evaluation System (DEA, 2017). It has encouraged all Government Departments at the national, provincial, and local level to develop climate change strategies and plans for adaptation and mitigation to the impacts of climate change. The government has been urging the research community to carry out climate change studies, which will assist in the monitoring and modelling of the climate change, as one way of informing the transition of South Africa to a climate-resilient country.

Two research institutions in South Africa mainly carry out climate change modelling studies. These institutions are Climate System Analysis Group (CSAG) at the University of Cape Town and the Council for Scientific and Industrial Research (CSIR) (Ziervogel *et al*., 2014). These two institutions use different climate modelling approaches. The CSIR uses dynamical downscaling through the variable-resolution global atmospheric model called the Conformal-Cubic Atmospheric Model (CCAM), which is a regional climate model (RCM). This model was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and is being used by CSIR to model present-day climate and future climate over Southern Africa and Tropical Africa (Engelbrecht, 2011).

As for the CSAG, this research institution uses statistical downscaling through the procedure that is presented in Hewitson & Crane (2006). To a limited extent, the institution has also used RCMs to downscale the climate variables from the GCMs (Ziervogel *et al*., 2014). Most of climate change studies in South Africa have utilised climate data from these two institutions, although statistically downscaled climate data has been more widely used than dynamically downscaled data (Hewitson *et al*., 2013).

One of the studies that have used downscaled data from these two institutions is the "Long-Term Adaptation Scenarios Flagship Research Programme (LTAS)" study conducted by the Department of Environmental Affairs of South Africa (DEA, 2013). This study determined the latest climate change trends and assisted in developing national adaptation scenarios for South Africa.

The DEA (2013) utilised the SRES and RCPs emission scenarios to which it was observed that mean annual temperature of South Africa had increased by at least 1.5 times above the average global temperature increase of 0.65 °C. At the same time, the frequency of extreme weather events had an increasing trend in the past five decades. The models showed warming trends in the future coupled with wetting and drying patterns in most parts of South Africa.

Kusangaya *et al*. (2014) also reported that most studies conducted in Southern Africa showed similar trends of hotter and drier future climate with significant impacts in interior and semi-arid parts of Southern Africa. Most of the biophysical sectors, like water resources, agriculture, health, infrastructure, biodiversity, and ecosystems, could be negatively affected. In this respect, the future climate is expected to worsen the slow growth of socio-economic developments due to significant vulnerability levels of South Africa (Ziervogel *et al.*, 2014).

Schulze (2011) emphasized that amongst the biophysical sectors, it is the water resources sector that the impacts of climate change are first felt before dispersing to the other sectors. It is prudent to warrant that adaption and mitigation measures of climate change should first be addressed in this sector. One of the ways of adapting to climate change is to conduct climate change impact studies in the water resources sector and then implement the outcomes that are derived from these studies.

WIDER (2016) is one of the climate change impact studies that was conducted at the national level in South Africa. This study showed that in the future, climate change is expected to cause changes in the average annual water runoff of -13% and +48% in the western and eastern parts of South Africa, respectively. This change in runoff could trigger an increase in water demands for irrigated agriculture and high evaporation rates in the water bodies of the western part of South Africa. At the same time causing more floods in the eastern part of South Africa.

Western Cape Province

The Western Cape Province is considered to have a varying pattern of rainfall with some areas having rainfall as low as 60 mm per year and others almost 3345 mm per year. This observation echoes well with Du Plessis & Scholms (2017), the study which showed that the trend of change in rainfall although not being clear, shows that western and eastern parts of Western Cape Province experience increased dry and wet rainfall pattern, respectively.

According to the Western Cape Provincial Government, there is a strong indication by most climate change models that the western part of Western Cape Province could be a dry area in the future years compared to the present-day years. This projection agrees with New's (2002) study that reported that some of the catchments in the western part of Western Cape like Langrivier, Bokkerivier, Willemnels and Kliensanddrif could have a reduction in mean annual runoff of 14%, 16%, 22% and 32%, respectively, by the year 2050. This change in runoff is expected to be caused by the reduction in mean annual precipitation of 10% and an increase in mean annual potential evaporation of 10%. This study used temperature and rainfall outputs of the GCMs that were forced by IS92a emission scenarios.

Steynor (2004) conducted a climate change impact study in the Breede River Catchment, which is also in Western Cape Province. The study used the climate data from GCMs which were forced by SRES A2 emission scenario to which it was observed that in future (2079-2099 period) relative to present (1979-1997 period), there will be a reduction in runoff in the Breede River Catchment due to climate change. This study emphasised that the impact of climate change will be more on the water requirement for irrigation than on municipal water use. There was no clear indication by the study on the magnitude of change of the mean annual runoff in the Breede River Catchment.

Louw *et al*. (2012) conducted a water resources study in the Breede and Berg Water Management Areas using the climate data from GCMs forced by SRES A1B and A2 emission scenarios. Their study compared the GCMs outputs of the present-day period (1971-1990) to 2011-2030 and 2046-2065, which were regarded as near and far future periods, respectively. The study established that in the future periods, there could be a 10% increase in temperature and potential evaporation in the catchments. This change in future climate could cause mean annual runoff in some rivers to increase between 1% to 20.8% while in others to decrease between 2.3% to 13.3%.

The study concluded that this divergence in the pattern of runoff was inconsistent with previous studies in the catchment. Previous studies (Schulze *et al*., 2005; Hellmuth & Sparks, 2005) indicated a reduction in mean annual runoff of 25% and 23%, respectively, based on the use of climate data from GCMs forced by A2, and A2 & B2 SRES emission scenarios, respectively.

The DEA (2013) study also highlighted the impact of climate change for the whole of South Africa. In Western Cape Province, the study focused on the Breede and Berg Water Management Areas (WMAs). The study used temperature and precipitation data which was statistically and dynamically downscaled from GCMs that were forced by SRES (A2 and B1) and RCPs (4.5 and 8.5) emission scenarios.

The study was comparing climate data of the future periods, which were short (2015-2035), medium (2040-2060), and long-term (2080-2100) to the present-day period (1971-2005). The study established that in all the scenarios, and using both statistically and dynamically downscaled climate data, the temperature is expected to have an increasing trend. In contrast, rainfall will not have a defined pattern with some areas receiving more rainfall and others less rainfall. The study also reported that there could be a reduction in mean annual runoff in all the rivers within the Western Cape Province in the future periods.

Pengelly *et al*. (2017) reported the impact of climate change in the Berg WMA. In their study, the impact of climate change was determined for 2025 and 2040 future periods using RCP 4.5 and RCP 8.5 based on GCM climate data downscaled by Climate System and Analysis Group (CSAG) from University of Cape Town. The study projected a reduction in the available water and an increase in future irrigation and municipal water demand in Berg WMA especially in the Western Cape Water Supply System (WCWSS). The increase in water demand was more pronounced in municipal water than irrigation considering that the WCWSS supplies more water for municipal use than to agriculture use in Berg WMA. The study also showed that evaporation is expected to increase in the future, while precipitation could have a diverging pattern.

Although the above studies have projected that climate change impacts in future will exacerbate the reduction of available water in Western Cape Province, the WIDER (2016) study reported that even under strong mitigation policies (that is when the emission of greenhouses in the atmosphere is controlled by the international community), the province will still have to deal with the impact of climate change in the water resources sector. This notion arose because it was noted that recovery from the impacts caused by climate change on water resources could be slow, considering that the province is a water-stressed area.

Eerste River Catchment

Eerste River Catchment is part of the Western Cape Province and lies within the Berg Water Management Area. Literature showed that Louw *et al*. (2012) were the only researchers who conducted a climate change impact study on the Eerste River using hydrological modelling. The study used the climate data generated by GCMs forced by SRES A1B and A2. The study modelled the Berg Water Management Area at sub-catchment level, which included the Eerste River Catchment. Using the ACRU hydrological model, the study showed a diverging pattern on Eerste River flows due to climate change with results indicating an increase and a decrease in mean annual runoff depending on the emission scenarios.

The range of change in mean annual runoff was between -13.3% and +20.4%. This diverging pattern was attributed to the few GCMs that were considered in the study. The study did not conclude on which direction the change in mean annual runoff could follow in the future and recommended no and low regret adaptions measure to be undertaken in the future. These measures provide more benefits at a low cost of implementation e.g. water governance.

It was concluded that there was no study on the climate change impacts on the Eerste River that had considered data generated from RCPs. These RCPs are regarded as the latest emission scenarios in the climate research community, as highlighted in Section 2.2.2.

2.3 Water Resources Development Scenarios

The water resources development scenarios are important instruments in developing possible future events that assist in planning, development, and management of the water resources (Dong *et al*., 2013). These scenarios are used to determine water demand based on socio-economic development and population growth. The idea of having scenario development originated from the military to which soldiers could formulate different scenarios that assisted in preparing for war.

Based on its successful application in the military, scenario development concept has been adopted in a wide range of developmental sectors (Dong *et al.*, 2013). Funke *et al*. (2013) reported that in South Africa, scenario development has assisted in strategic planning and advancement of a common understanding of water resources development among people of different knowledge in the water sector. In this respect, the next sections present the development scenarios of water resources for the Western Cape Province and Stellenbosch Municipality.

2.3.1 Overview of Water Resources Development Scenarios in Western Cape

The Western Cape Province is mainly supplied with water from the Western Cape Water Supply System (WCWSS) which is operated by City of Cape Town and Department of Water and Sanitation (DWS). This water supply system comprises interlinkages of dams, tunnels, reservoirs, bulk water supply pipelines, water treatment works and distribution networks. The WCWSS supplies water to Stellenbosch, Paarl, Greater Cape Town, Wellington, Swartland and towns on the West Coast. Some of the irrigators in Eerste, Berg and Riviersonderend Rivers also get water from the WCWSS (DWAF, 2007b).

The dams that feed the WCWSS include the Berg, Wemmershoek, Voëlvlei, Theewaterskloof, Steenbras Lower and Steenbras Upper with storage capacity of 127 Mm^3, 58 Mm^3, 158 Mm^3, 432 Mm^3, 34 Mm^3, and 30 Mm^3, respectively. This means the WCWSS has a total water storage of 839 Mm^3 (DWS, 2014).

The primary sources of water to the WCWSS are Breede and Berg Rivers which are supplemented by the Eerste, Palmiet and Steenbras Rivers as well as groundwater. The WCWSS is designed with the operational philosophy of minimising spillage during winter rainfall season when the demand is low and maximising storage for the summer season when the demand is high. Spillage of dams is allowed when all dams are full and system demand is guaranteed to be met. 50% of the dam storage is used to meet the annual water demand, while the remaining 50% is used as a reserve for periods of drought (DWAF, 2007b). One of the ways that facilitate this design approach is the use of the Riviersonderend-Berg River Government Water scheme, which is an inter-basin water transfer scheme between the Breede and Berg River Catchments in the WCWSS.

This Riviersonderend-Berg River Government Water Scheme uses a tunnel system that conveys water from Theewaterskloof Dam (located in Sonderend River) to Berg River through Franschhoek Mountain then to Kleinplaas Dam which is located in Eerste River. From the Kleinplaas Dam, the tunnel passes through Stellenbosch Mountain which is then joined with bulk water supply pipelines all the way to water treatments works located within the City of Cape Town. In the summer season, the tunnel system supplies water from Theewaterskloof Dam to the City of Cape Town. During the winter season, the tunnel system conveys water to Theewaterskloof Dam from the Berg River and surrounding tributaries.

In the WCWSS, the Kleinplaas Dam is regarded as the balancing dam because it balances the supply of water to City of Cape Town, Stellenbosch Town and the irrigators in the Eerste River from the Riviersonderend-Berg River Government Water Scheme. The Kleinplaas Dam is operated by maintaining the water level at about 0.8 m below the full supply level.

If the water level falls below 0.8 m, a situation that usually occurs in the summer season, the three-needle valves from the tunnels of Riviersonderend-Berg River Government Water Scheme releases the water to Kleinplaas Dam to supplements the existing water in the dam in meeting the water requirements assigned to this dam. In the winter season, water is temporarily stored in the Kleinplaas Dam and is diverted to the City of Cape Town (Van Zyl, 2020).

In 2007 the Department of Water Affairs in South Africa conducted the Western Cape Water Supply Reconciliation Strategy Study (WCWS-RSS) as a decision support tool for the reconciliation of the future water demand and supply in the WCWSS. The WCWSS-RSS was necessitated by the increase in annual water demand which was triggered by economic and population growth of the Western Cape Province, especially in the City of Cape Town. The rate of increase in annual water demand was between 2% and 3% per annum.

The WCWS-RSS highlighted two water requirement scenarios denoted as high and low, which were based on the forecasted economic and population growth rates from 2006 to 2030. The high water requirement scenario projected an increase of mean annual water demand of 3.09%, population and economic growth rates range of 1.12% to 1.74%, and 4.5% to 6%, respectively. As for the low water requirement scenario, it had a water demand projection of 1.43%, population growth rates range of 0.16% to 0.7%, and economic growth rate of 4% (DWAF, 2007b).

Based on these two scenarios, it was projected that the water demand in WCWSS would equal the available water in 2011 and 2017 for the high and low water requirement scenarios, respectively, even when the net 1:50 year system yield was supplemented from 475 Mm^3/a to 556 Mm^3/a with the construction of the Berg Dam. In both water requirement scenarios, future irrigation water requirement was projected to be growing at a steady rate of 2% per annum up to the DWS capping water allocations for irrigation use in Western Cape. Figure 1 presents the projection of the high and low water requirement scenarios in the WCWS-RSS, including the historical water use in the WCWSS.

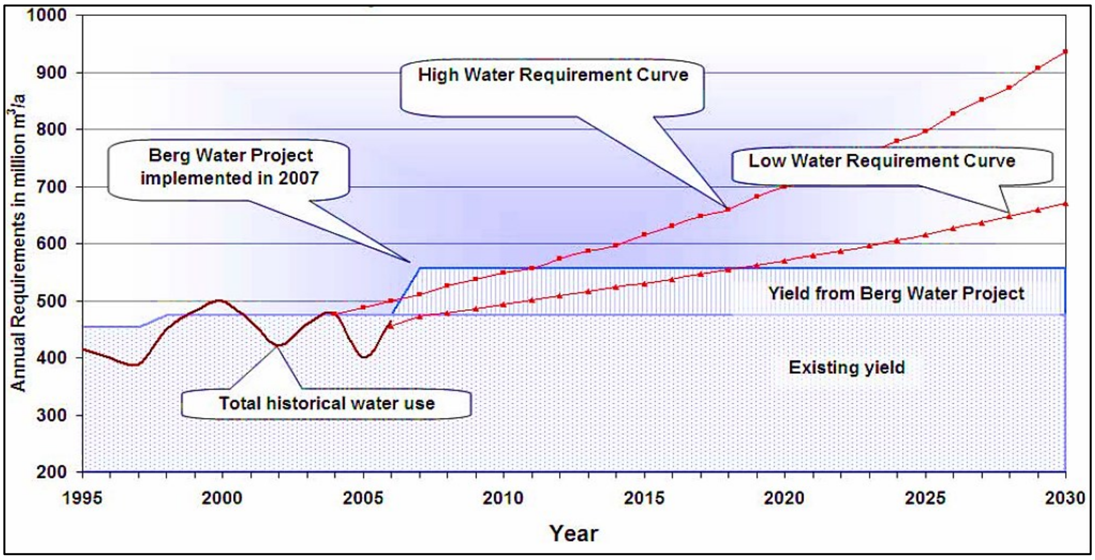

Figure 1: High and Low Water Requirement Scenarios (Source: DWAF, 2007b)

Based on these two water requirement scenarios, the WCWS-RSS presented different interventions that could assist in reconciling the water demand and supply. Some of the interventions were the implementation of City of Cape Town water conservation and water demand management, development of Berg River-Voëlvlei Dam Augmentation Phase 1, development of Cape flats and Newlands aquifers. Raising the Steenbras Lower Dam, re-use of treated effluent, and developing diversions of Lourens River, Eerste River, Upper Wit River, Upper Molenaars, and Michell's Pass were also some of the proposed interventions.

The successful implementation of the City of Cape Town water conservation and water demand management (WC/WDM) resulted in a downward trend in water use from 2011 to 2013, such that in 2014 the water requirement scenarios were updated. Therefore, the annual growth rates of high and low water requirement scenarios were revised to 3.38% and 2.3%, respectively, for the period 2013 to 2040 (DWS, 2014).

It should be noted that the revision of the growth rates in water requirement for both scenarios was mainly due to anticipated changes in future municipal water demand, especially for the City of Cape Town. The projected 2% growth rate of future water requirement for irrigation use up to the capped water allocations as determined in the WCWS-RSS study of 2007, was maintained as highlighted above.

In addition to the revision of growth rates for high and low water requirement scenarios, DWS together with the City of Cape Town also investigated three water reconciliation scenarios. These reconciliation scenarios were denoted as Base Scenario (High Growth with 100% successful WC/WDM), Planning Scenario (High Growth with 50% successful WC/WDM), and Worst-Case Scenario (High Growth and Climate Change).

In Worst-Case Scenario, it was noted that if water conservation and water demand management measures are continuously implemented, and climate change reduces 15% of the available water in WCWSS, there will be a shortage of water in areas supplied by WCWSS. This water deficit is expected to occur in 2021 and 2019 for low and high water requirement scenarios, respectively (DWS, 2014). The DWS (2014) also highlighted that this Worst-Case Scenario was very costly and required new interventions to the ones that were initially identified in DWAF (2007b) as highlighted above.

It was then considered that the Worst-Case Scenario should only be implemented when there is proof that long term rainfall is decreasing, and that the impacts of climate change on water resources are well understood. Therefore, of the three water reconciliation scenarios, the Planning Scenario was the one that was adopted because some of the interventions that were identified by the DWAF (2007b) could assist in reconciling the water demand and supply by 2020 and 2022 for low and high water requirement scenarios, respectively.

The Planning Scenario also assumed the attainment of 50% of WC and WDM, which was regarded as more realistic than the assumption made in Base Scenario of 100% achievement of WC/WDM (DWS, 2014). Figure 2 presents the revised high and low water requirement scenarios for 2013 to 2040 period based on Planning Scenario.

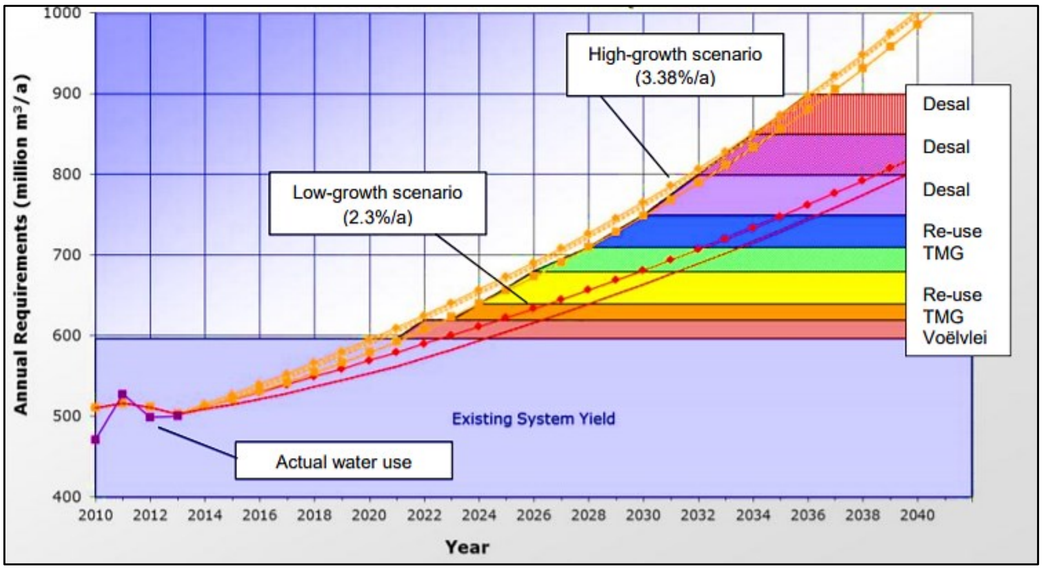

Figure 2: Revised High and Low Water Requirement Scenarios (Source: DWS, 2014)

To implement the Planning Scenario, the DWS (2014) recommended that the Berg River-Voëlvlei Dam Augmentation scheme should be in place by 2020 to supplement the existing system yield for the WCWSS. Besides, Table Mountain Group Aquifer, Re-use of treated water, and desalination were also prioritised as immediate interventions to be implemented amongst other interventions highlighted in DWAF (2007b).

2.3.2 Overview of Water Resources Development Scenarios in Stellenbosch Municipality

The Stellenbosch Municipality is located in Berg Water Management Area and consists of Stellenbosch Town, Klapmuts, Franschhoek, Dwarsrivier and surrounding rural areas. The Municipality gets its water supply from Eerste River, WCWSS, and the City of Cape Town Water system with supply allocation of 40%, 30% and 30%, respectively (Stellenbosch Municipality (SM), 2018). The Stellenbosch Town is supplied with water from Eerste River and WCWSS. The water supplied to the Stellenbosch Town is approximately 70% of the total water supplied to the Stellenbosch Municipality. The water from Eerste River is abstracted upstream of Kleinplaas Dam in Jonkershoek Mountains, then transferred to Idas Valley Dams, and Water Treatment Works through bulk water pipelines. The water is then distributed to the Stellenbosch Town from the Idas Valley Water Treatment Works.

As for the water supplied from WCWSS, this water is supplied through the Riviersonderend-Berg River Government water scheme which transfers water from Theewaterskloof Dam to Kleinplaas Dam using tunnels. The water from Kleinplaas Dam is then transmitted through Stellenboschberg Tunnel to bulk water pipelines which then conveys raw water to Paradyskloof Water Treatment Works. The water from Paradyskloof Water Treatment Works is again distributed to the Stellenbosch Town.

The increase in water demand due to socio-economic development in the Western Cape Province highlighted in Section 2.3.1 was also noted in the Stellenbosch Municipality. The SM (2017a) has projected that the water demand in Stellenbosch Municipality for the period 2014 to 2034 would increase at 3% and 2% per annum for the medium and low growth development scenarios, respectively. The water demand for Stellenbosch Municipality is expected to be 27,453 Ml/a by 2034 based on the medium growth scenario. Therefore, it is expected that the available water resources of 17,973 Ml/a will be met in 2021 and 2025 in the medium and low growth scenarios, respectively. Figure 3 presents the projected water demand for Stellenbosch Municipality for the low and medium growth scenarios.

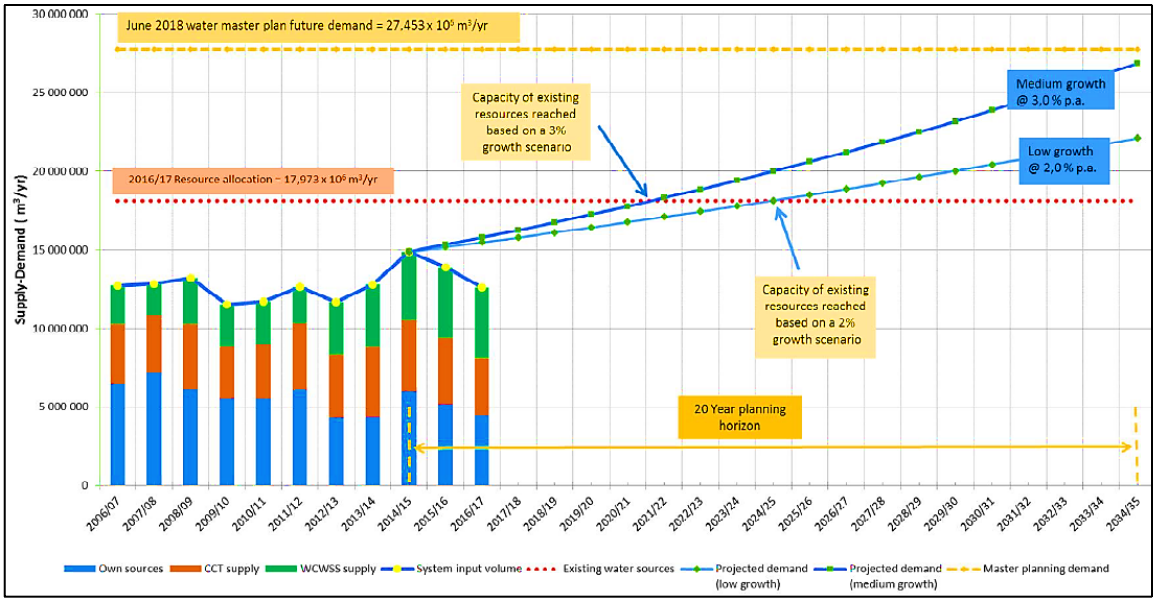

Figure 3: Projected Water Demand for Stellenbosch Municipality (Source: SM, 2017a)

As for the Stellenbosch Town, the SM (2017a) reported that by 2034, the available water resources of 10,224 Ml/a which is a summation of water allocation of 7,224 Ml/a and 3,000 Ml/a from Eerste River and WCWSS, respectively, is expected to be inadequate to meet the projected water demand of 15,706 Ml/a. To meet this demand and plan for a drought situation, several alternative options were proposed in the SM (2018) and SM (2017a) studies.

Some of the options were to augment the available water resources with potential groundwater resource of 1,598 Ml/a, and to increase the water abstraction volume from the Eerste River. Other options were connecting the water distribution network of Stellenbosch Town to Blackheath Water Treatment Works and implementing trade-off of water allocated to irrigation water use from WCWSS with treated wastewater from Stellenbosch Wastewater Treatment Works (Stellenbosch WWTW).

In the water trade-off arrangement, the Wynland Water Users Association, which regulates water allocation to irrigators in Eerste River catchment, could be allocated treated wastewater from the Stellenbosch WWTW in exchange for compensation water releases for irrigation from the WCWSS at Kleinplaas Dam. In this way, the allocation of raw municipal water at Paradyskloof Water Treatment Works from the WCWSS could increase.

SM (2018; 2017a) did not show the quantity of additional water that could be abstracted from the Eerste River to meet the projected 2034 water demand let alone for drought situations. This uncertainty becomes more direful considering that the WCWS-RSS also recommended Eerste River Diversion as one of the interventions to be implemented to supplement the available water resources of the WCWSS.

This Eerste River Diversion project will consist of a 4m high concrete weir with 35,000m^3 capacity on Eerste River from which water will be pumped to an off-channel balancing dam at the rate of 4 m^3/s. The water will then be pumped from the balancing dam to Faure Water Treatment Works through 2.2 km bulk water pipeline. At Faure Water Treatment Works, the water will then be connected to the existing water distribution network of the WCWSS. Through this project, it is expected that about 8.3 Mm^3/a yield could be diverted from the Eerste River with consideration to ecological water requirements (DWAF, 2007b).

2.3.3 Future Water Requirements for Irrigation in Western Cape Province

The current sources of water for irrigation in Western Cape Province are run of the river, farm dams and inter-basin water transfer from WCWSS. The DWS has capped the water allocation for irrigation use to all irrigation boards and Water Users Associations (WUA) in the province. These water allocations are put in place to assist in maximising the water supply and the demand such that there is efficient use and high assurance of water supply to farmers.

The National Water Resources Strategy 1 (NWRS1) DWAF (2004a) in projecting its base and high water requirement scenarios up to 2025, reported that water allocations to irrigated agriculture by DWS in Western Cape Province would remain the same. The DWAF (2004b) study reported that the assumption inherited in the NWRS1 of no growth in future water requirement for irrigation in the province, especially in Berg Water Management Area (Berg WMA), could be correct as long as the unexercised water allocations in WCWSS are fully utilised. This study recommended that the unexercised water allocations by farmers should be investigated because the water from these allocations could assist in meeting potential growth of future water requirements for irrigation.

The DWAF (2004b) also reported that in Berg WMA at least 50% of the farmers use farm dams and run of the river as a source of water in their irrigation schemes. The study indicated that there is a possibility that the future water requirements for irrigation could increase especially in the irrigation schemes that do not depend on WCWSS because it is a challenge to regulate the water use of these farmers. The study did not show any growth rate for the future water requirements in the irrigation areas that do not use water from WCWSS.

In the National Water Resources Strategy 2 (NWRS2) DWA (2013) (the updated version of NWRS1) the same assumption of no growth in water requirements for irrigation as adopted in NWRS1 was also upheld up to 2030. NWRS2 also projected that smallholder irrigation schemes are expected to use the same current amount of water in the future. The NWRS2 reported that additional water allocation in the future could only happen if there is water use efficiency in the current irrigation schemes.

The Irrigation Strategy (Department of Agriculture, Forestry and Fisheries, 2015), was noted to agree with NWRS2 when it also reported that there is no expectation that irrigation schemes in Western Cape Province could expand in the future based on the available water. The Irrigation Strategy indicated that there is a possibility of increasing irrigation area in the province by 5000 ha only if Clanwilliam Dam is raised to support the additional hectarage, considering that the province is a water-stressed area.

Department of Environmental Affairs and Development Planning (DEA & DP) (2015) reported that there is a high chance that the expectation of raising of Clanwilliam Dam will take some time to be realised. In this regard, the availability of additional water in the Western Cape Province that can allow expansion of irrigated agriculture might not be possible in a short period. The DEA & DP (2015) proposed exploration of groundwater, treated wastewater and desalination as possible alternatives to surface water if irrigated agriculture is to expand in the province.

DWAF (2007b) and DWS (2014) which are the reconciliation strategy for the WCWSS and the updated status of the same reconciliation strategy, respectively as highlighted in Section 2.3.1, projected that in the low and high water requirement scenarios, future irrigation water requirement is expected to grow. The growth in irrigation water requirement is anticipated to be 2% per annum until the capped water allocations for irrigation use from WCWSS, as guided by DWS are attained. Once the capped water allocations are fully utilised, it is expected that there will be no more water available to allocate for irrigation use in Western Cape Province from the WCWSS.

Pengelly *et al*. (2017) also acknowledged that most catchments in Western Cape Province are considered “constrained” because the available water is already committed to different uses. Pengelly *et al*. (2017) reported that there is a possibility that future water demand for irrigated agriculture might increase due to climate change such that in Berg WMA, the water demand for irrigation could increase by 33% in 2040.

Based on the above information, it is expected that future water requirement for irrigation use in Western Cape Province from WCWSS might not grow. This observation is due to the lack of available water to meet the irrigation demands. There is a possibility that at a small scale, especially for farmers that depend on farm dams and run of the river as a source of water for irrigation use, future water requirements might increase. However, the growth rate of water requirements is not known.

3. Description of Study Area

This section presents the research setting for this research which was the Eerste River Catchment.

3.1.1 General Description of Eerste River Catchment

The Eerste River is one of the rivers in the Berg Water Management Area, Western Cape Province, South Africa, as presented in Figure 4.

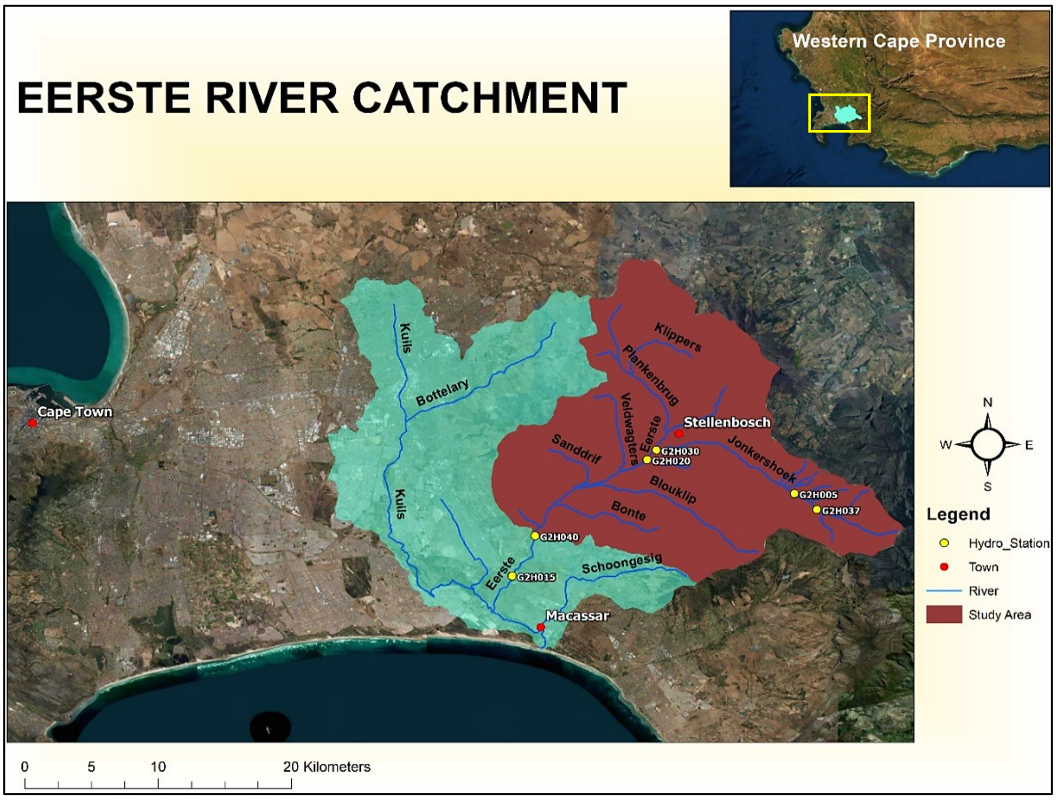

Figure 4: Location of Study Area

It originates from the Jonkershoek Mountains in Jonkershoek Forest Reserve at an altitude of 520 m (Ngwenya, 2006). The river flows from the Jonkershoek Mountains in a north-westerly direction towards Stellenbosch to which it then changes southwards passing through agricultural land until it discharges into the Atlantic Ocean at False Bay near Macassar (Meek *et al*., 2013). In this respect, it is located in the G22F, G22G, G22H and G22E quaternary catchments.

The Eerste River is approximately 40 km long and has a catchment area of 420 km^2. The river has an average slope of 24 m/km and 2 m/km, and the width of 5 m and 14 m in its upper and lower reaches, respectively (Meek *et al*., 2013). The main tributaries of Eerste River are Klippers, Plankenbrug, Krom, Jonkershoek, Sanddrif, Blouklip, Bonte, Veldwagters, Schoongesig and Kuils Rivers.

Amongst these tributaries, the Kuils River is the major tributary of the Eerste River with a catchment area of approximately 120 km^2. The Kuils River has the Bottelary River as its primary tributary (Heydorn & Grindley, 1982). The total catchment area of Eerste and Kuils Rivers denoted as Eerste-Kuils River is 640 km^2.

The DWS has installed hydrological gauging stations in Eerste River which are used to monitor the flow. These hydrological gauging stations, in the order from the source to the mouth of the river, are G2H037, G2H005, G2H020, G2H040 and G2H015. Although G2H015 is the furthest gauging station in the catchment, it is currently not operational. The current hydrological monitoring of the Eerste River ends at the G2H040 gauging station. Apart from the four operational hydrological stations in the Eerste River, there is also a monitoring station for the diversion of water from Eerste River to an irrigation canal which is denoted as G2H030. In this research, the location of the study area was from the Jonkershoek Mountains up to G2H040 hydrological station, as presented in Figure 4.

3.1.2 Geology

The geology of the greater area of the Eerste River Catchment comprises undulating hills with fertile soils overlaying the Cape Granite and Malmesbury Shale, and also, the scattered deposits of gravel, sandstones, conglomerates and irregular developments of silcrete and calcrete (Heydorn & Grindley, 1982). The upper and lower reaches of the Eerste River are considered to lie on folded Quartzitic Table Mountain Sandstone, and Cape Granite with low-lying coastal plain on Aeolian Sands, respectively (Meek *et al*., 2013).

Based on the above geology of the Eerste River catchment, surface runoff is more predominant than subsurface flow in the upper reaches while in the lower reaches, it is the opposite. Therefore, the water table is considered to be higher in the lower reaches than in the upper reaches (Heydorn & Gridley, 1982).

3.1.3 Climate

The Eerste River Catchment experiences Mediterranean Climate. 85% of rainfall occurs in June to September such that the Eerste River Catchment is characterised with winter rainfall which is influenced by South Atlantic Anticyclones (Chingombe, 2012). The leading cause of this winter rainfall is the combination of northward high-pressure systems and cold Benguela current (Du Plessis & Scholms, 2017).

The catchment also experiences orographic rainfall which dominates east of the catchment around the Jonkershoek, Hottentots Holland and Groot Drakenstein Mountains. This east part of the catchment experiences the highest rainfall of the catchment which is approximately 1700 mm/a, especially in the month of June while the west side of the catchment receives less rainfall, amounting to 400 mm/a (Chingombe, 2012).

The winter season is cold and wet with the occurrence of gale-force north-westerly winds which results in snow forming on top of the surrounding mountains. The summer season is hot and dry with daily temperatures sometimes reaching up to 40°C with the occurrence of predominant strong south-easterly winds (Matshakeni, 2016). The Eerste River Catchment has varying MAE which depends on the quaternary catchments that encompass the catchment. This MAE ranges between 1410 mm/a to 1450 mm/a. Based on the above information, the catchment is considered to experience similar evaporation and rainfall of the 23C and G2C zones of South Africa, respectively.

3.1.4 Land Use and Land Cover

The land use and land cover in Eerste River Catchment is dominated with agriculture areas, mainly vineyards and orchards. It also includes commercial forestry, communal grazing, built-up areas (residential and industrial), farm dams and nature conservation (grasslands and natural forests) (Meek *et al*., 2013, Chingombe 2012).

Several studies have reported an increase of built-up areas in the catchment like the golf course, sports fields, residential houses, and commercial buildings due to urbanisation, especially in Stellenbosch in the past two decades. This increase in urbanisation has caused a reduction in nature conservation and farmland areas in the catchment, and there are fears that this might continue to shrink natural environments, e.g. natural forests (Kula, 2007; Tizora *et al*., 2016).

3.1.5 Water Resources

In the Eerste River Catchment, surface water predominates as the primary source of water supply for municipal and irrigation water use. In this section, water resources will be described based on municipal use in the catchment. Irrigation use is described in detail in Section 3.1.6, which deals with agriculture in the Eerste River Catchment. Stellenbosch is supplied with municipal water from the Eerste River but capped at 7.224 Mm^3/a by DWS. This municipal water is abstracted at the intake weir located upstream of the G2H037 gauging station in the area upstream of the Kleinplaas Dam, and is conveyed through gravity pipeline to Idas Valley Water Treatment Works (WTW) for treatment, and also to two Idas Valley Dams for storage.

In the summer season, when the water levels are low in Eerste River, the abstracted raw water from the Eerste River to the Idas Valley WTW is augmented with water from Idas Valley Dams. The treated water at Idas Valley WTW is then distributed to the Stellenbosch (SM, 2017b). The Idas Valley Dams with a combined storage capacity of approximately 2.382 Mm^3 and Idas Valley WTW with a treatment capacity of 28 Ml/day are located 2.5 km north-east of Stellenbosch Town close to Krom River (Heydorn and Grindley, 1982; SM, 2017b; SM, 2018). Figure 5 presents the water and wastewater network in the catchment.

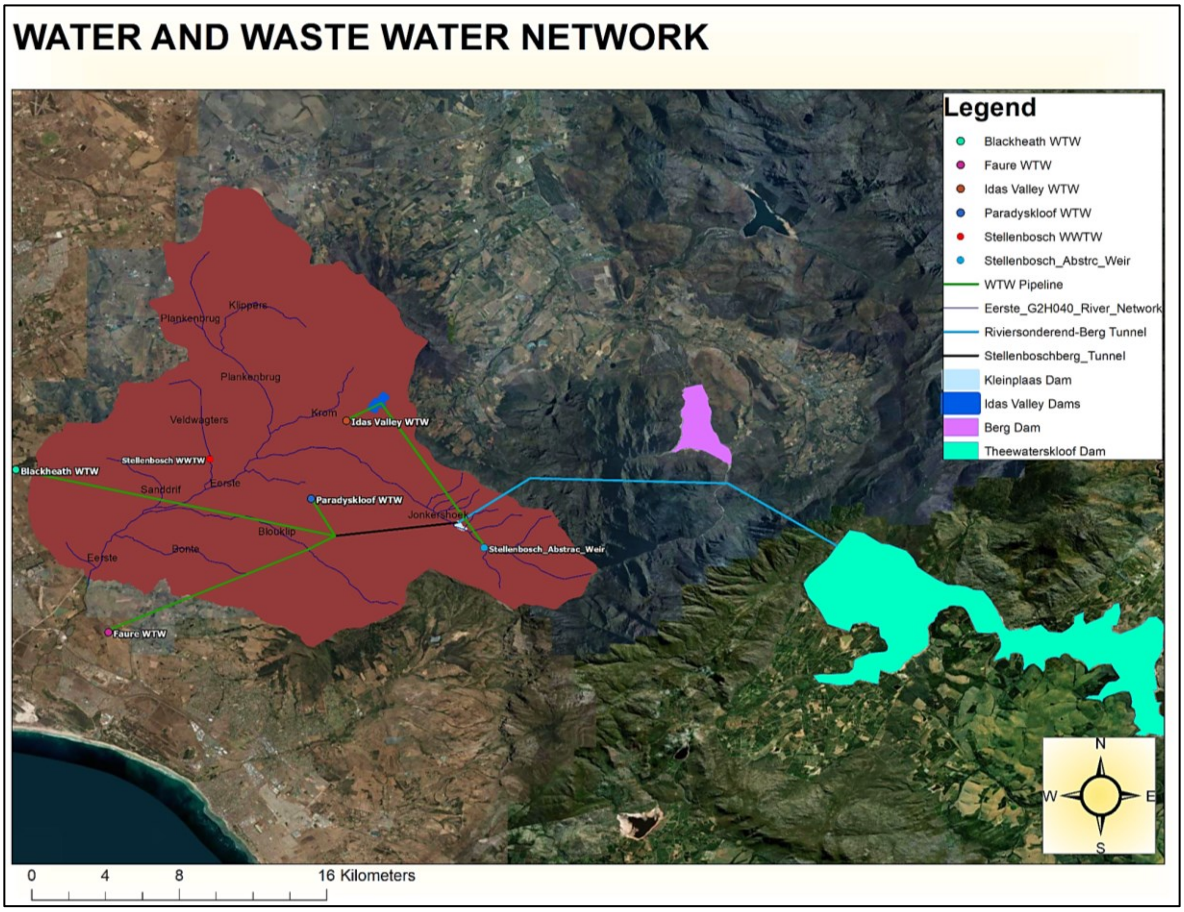

Figure 5: Water and Wastewater Network in Eerste River Catchment

Stellenbosch also benefits from the raw water supplied to WTWs from the WCWSS through the Riviersonderend-Berg River Government Water Scheme. The WTWs that receive water from WCWSS are Paradyskloof, Blackheath and Faure (DWAF, 2007c). The water treated at Blackheath and Faure WTWs is supplied to the City of Cape Town while that at Paradyskloof WTW is supplied to Stellenbosch Town. The raw water that is supplied to Paradyskloof WTW from the WCWSS is capped at the rate of 3 Mm^3/a by DWS and is treated at the rate of 10 Ml/day before it is conveyed to the water distribution network of Stellenbosch Municipality (SM, 2017b).

As for the wastewater in Eerste River Catchment, it is treated at Stellenbosch Waste-Water Treatment Works (WWTW). The hydraulic design capacity of Stellenbosch WWTW was upgraded from 20 Ml/day to 35 Ml/day in early 2020. The treated effluent from Stellenbosch WWTW is conveyed to Eerste River through Veldwagters River and contributes significantly to the available water in the river during summer season (Ngwenya, 2006; Meek *et al*., 2013, Malisa *et al*., 2018). The Eerste River also receives untreated high pollutant load from informal settlements and industrial areas through the Plankenbrug River. The water chemistry of the Eerste River is regarded to be of poor quality in the lower reaches (Ngwenya, 2006; DWAF, 2007d). Figure 5 presents the water and wastewater network in the catchment.

3.1.6 Agriculture

Most of the land in Eerste River Catchment is used for agricultural purposes, especially for vineyards, and to a lesser extent, orchards, and vegetables (DWAF, 2008b). The vineyards in the Stellenbosch area, which is part of this catchment, covers 16% of the total area under vineyards in South Africa. In this respect, viticulture that is practised in this catchment, contribute significantly to the socio-economic development of South Africa through the export of wines and wine tourism of the Cape Winelands (SAWIS, 2018).

The Wynland Water Users Association (WUA) is the organisation that manages the water allocation to farmers in the catchment. This organisation is composed of three irrigation boards which are Helderberg, Stellenbosch and Lower Eerste River or Eersterivier (South African Irrigation Institute (SABI), 2013). Figure 6 presents the location of irrigation areas under Wynland WUA.

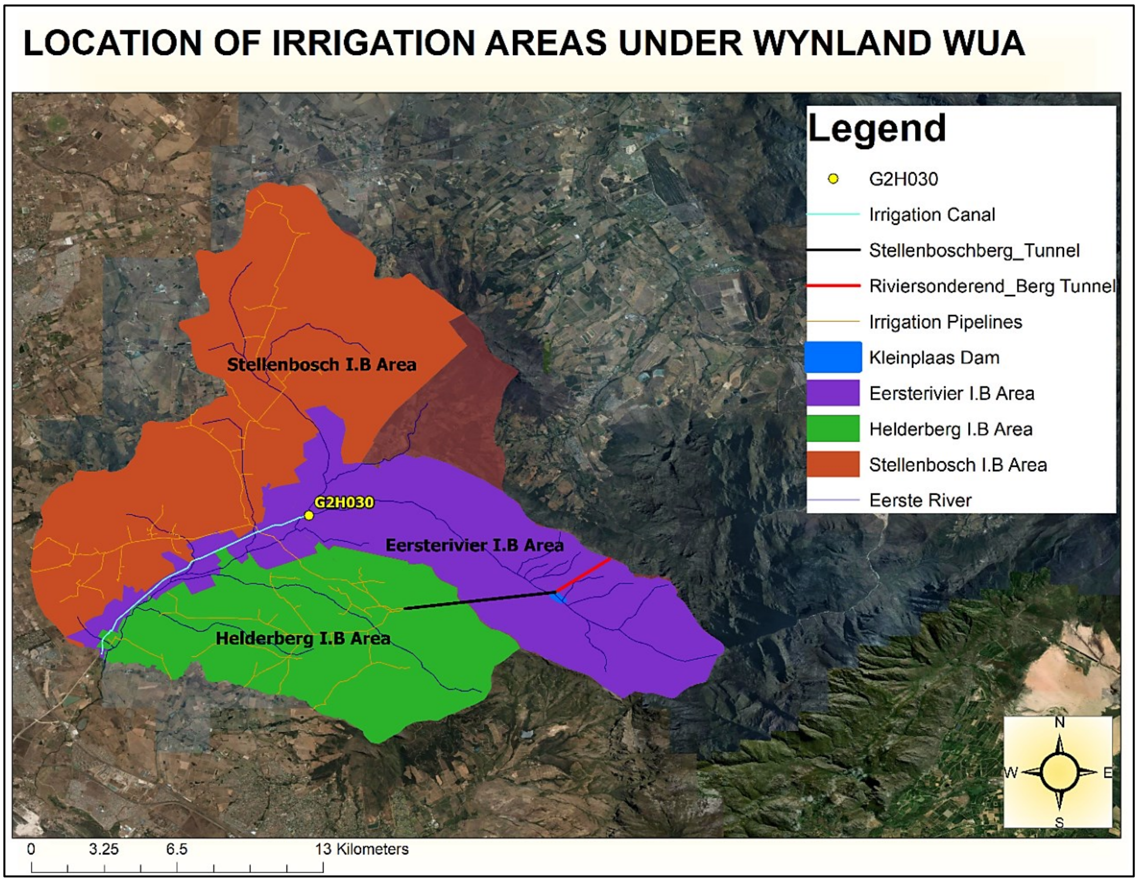

Figure 6: Location of Irrigation Areas under Wynland WUA

Through the Wynland WUA, farmers are registered based on three sources of water for irrigation. These sources are farm dam (direct rainfall), Eerste River (direct from the river) and WCWSS through the Riviersonderend-Berg River Government Water Scheme. Based on Eerste River as the source of water for irrigation, irrigators abstract water from the river as well as compensation water releases for irrigation from WCWSS through Kleinplaas Dam.

The water released from Kleinplaas Dam to Eerste River is regarded as "compensation water release" because it compensates water abstracted upstream of the Kleinplaas Dam from the river by the Stellenbosch Municipality for municipal water use (Meek *et al*., 2013). These compensation water releases flow downstream of the dam and are used by farmers along the river, especially those in the Lower Eerste River (Eersterivier) Irrigation Board. There is a hydrological monitoring station denoted as G2H030 at the confluence of Plankenbrug and Eerste Rivers to which water diverted from Eerste River to the canal for irrigation use, is measured. This canal is approximately 15 km long. Most water from Eerste River is diverted in winter season due to low flows in summer season and is stored in farm dams to supplement the low flows in summer season for irrigation use (Van Zyl, 2020).

DWS allocated a capped water use of 4000 m^3/ha/a which is approximately 3.1 Mm^3/a to Lower Eerste River Irrigation Board from Riviersonderend-Berg River Government Water Scheme. The allocated water to the Eersterivier Irrigation Board is the compensation water released from Kleinplaas Dam to the Eerste River and is distributed to 514 ha. The compensation water has been released from the dam since the dam was constructed in 1982.

The water from WCWSS is also distributed to farmers in Helderberg and Stellenbosch Irrigation Boards. The water distribution to these two irrigation boards is different from the Lower Eerste River Irrigation Board, which has been explained above. In this case, the water is released from Kleinplaas Dam through Stellenboschberg tunnel outlet and is then distributed through pipelines to the farmers in Helderberg and Stellenbosch Irrigation Boards. These distribution pipelines are approximately 56.84 km and 115.62 km long in Helderberg and Stellenbosch Irrigation Boards, respectively (SABI, 2013).

The allocated water from this source is also capped at 4000 m^3/ha /a by DWS which translates to capped annual irrigation volumes of 12.1 Mm^3 and 12 Mm^3 distributed to 3017.4 ha and 3010.1 ha in Helderberg and Stellenbosch Irrigation Boards, respectively (DWS, 2014; SABI, 2013). These irrigation boards started receiving water from WCWSS in 1992, and the estimated average monthly distribution pattern is presented in Table 2.

Table 2: Distribution of Water to Helderberg and Stellenbosch Irrigation Boards

Month	Distribution Percentage (%)
October	4.9
November	7.5
December	6.9
January	18.9
February	15.7
March	17.7
April	11.1
May	6.1
June	4.2
July	2.8
August	1.6
September	2.6

Water allocation quota to Wynland WUA from WCWSS by DWS depends on the available water in the WCWSS. The Wynland WUA was allocated 4000 m^3/ha/a, 2800 m^3/ha/a, and 1300 m^3/ha/a in 2009-2016, 2017 and 2018, respectively. Sometimes the farmers do not fully utilise their "capped water allocation" from WCWSS as a strategy to have a consistent higher assurance of water supply to their crops in case of droughts or dry spell. During droughts, the unexercised portion of the "capped water allocation" can be released to be allocated to other competing water uses like municipal water without having significant impacts to the farmers in the catchment (DWAF, 2007b).

The allocation of water for irrigation use from farm dams (direct rainfall) is based on the irrigation water requirements and the reservoir capacity of the farm dams. These farm dams are supposed to be registered with DWS. Farmers in the Eerste River Catchment also practice winter filling of farm dams as reported by DWAF (2008a). In this practice, farmers when they project that the farm dams will not be filled during the winter season due to direct rainfall, they can fill the dams from the nearby rivers. Most of the farm dams are located in G22G and G22H quaternary catchments, with some in G22F quaternary catchment.

3.1.7 Vegetation

The primary vegetation in the catchment is natural fynbos and to a lesser extent forestry plantation of Pinus Radiata (Pine trees) (Meek *et al*., 2013). This natural fynbos is mainly found in the upper reaches of the Eerste River, especially along the river banks and is used as a buffer zone between forestry plantation and the river. Oak trees, to some extent, are found in Stellenbosch town due to their historical importance to this town.

The Black Wattle and Eucalyptus predominate as invasive alien plant (IAP) species in the Eerste River Catchment especially in the sub-catchment of Krom River, which is a tributary to Eerste River (DWAF, 2008b). DEA (2016a) reported that to a lesser extent pine is also considered as IAP if the rotation periods of pine is over 15 years. However, most of the time pine is regarded as part of commercial forestry.

These IAPs are considered to have a high affinity of water such that they tend to reduce the available mean annual runoff of the rivers in the catchment. In this respect, the removal of AIPs was integrated as part of the water supply management by the Government of South Africa to increase the available water in catchments (Cullis *et al*., 2007).

4. Methodology

This chapter presents the methodology that was adopted for this research. The overview of the research methodology and data collection are described in the following sections.

4.1 Overview of the Research Methodology

The Pitman model (version 2.11) also known as WRSM2000 model, and three modelling periods which were 1983-2018, 2022-2057, and 2058-2093 representing present-day, near-future and far-future periods, respectively, were adopted for this research. The Pitman model was selected because it has been used before in the Eerste River Catchment and is still being used in the water resources planning in South Africa (DEA, 2016a). Besides, the available data that was collected was in "monthly" format, which meant that the Pitman model was a suitable model to be used in this research because it runs on a monthly time step.

The 1983-2018 period was adopted to be the present-day period to include the entire period that the Kleinplaas Dam has been in existence in the Eerste River. The 1983-2018 period was also regarded as the period in which a new flow regime developed in the Eerste River. This notion emanated from the understanding that the construction of the Kleinplaas Dam in 1982 might have changed the flow regime of Eerste River. The future periods were determined to maintain the same number of years as the 1983-2018 period which was 35 years, and also to have a period that is over 30 years which is regarded as a classical period to determine the impact of climate change (Solomon *et al.*, 2007). Thus, 2022-2057 and 2058-2093 periods were adopted as future periods.

The Pitman model was calibrated and validated using the data collected and analysed. The present-day naturalised flow in the Eerste River was then modelled. The modelling of the impacts of climate change and development scenarios on the Eerste River was done in three phases. The first phase was on modelling the impacts of climate change on Eerste River flows based on the future climate in 2022-2057 and 2058-2093 periods. The second phase was on modelling the impact of development scenarios on the Eerste River for the 2022-2057 period. As for the third phase, the modelling was on the combined impact of climate change and development scenarios on Eerste River flow for the 2022-2057 period.

In these three phases, the impact on the Eerste River was determined by comparing the simulated mean annual flows of the climate change and development scenarios to that of the present-day period. The climate data used in the first and third phases were from an ensemble of 11 GCMs of CMIP5, which had been forced by RCP 4.5 and RCP 8.5.

In this research, the changes that could arise in the future irrigation and municipal water demand due to the impact of the climate change on Eerste River flows were determined. The Top-Down approach of modelling the climate change on the Eerste River was adopted in this research because the climate outputs from the GCMs were driving the modelling process. Based on the above information, Figure 7 presents the methodology framework that was adopted.

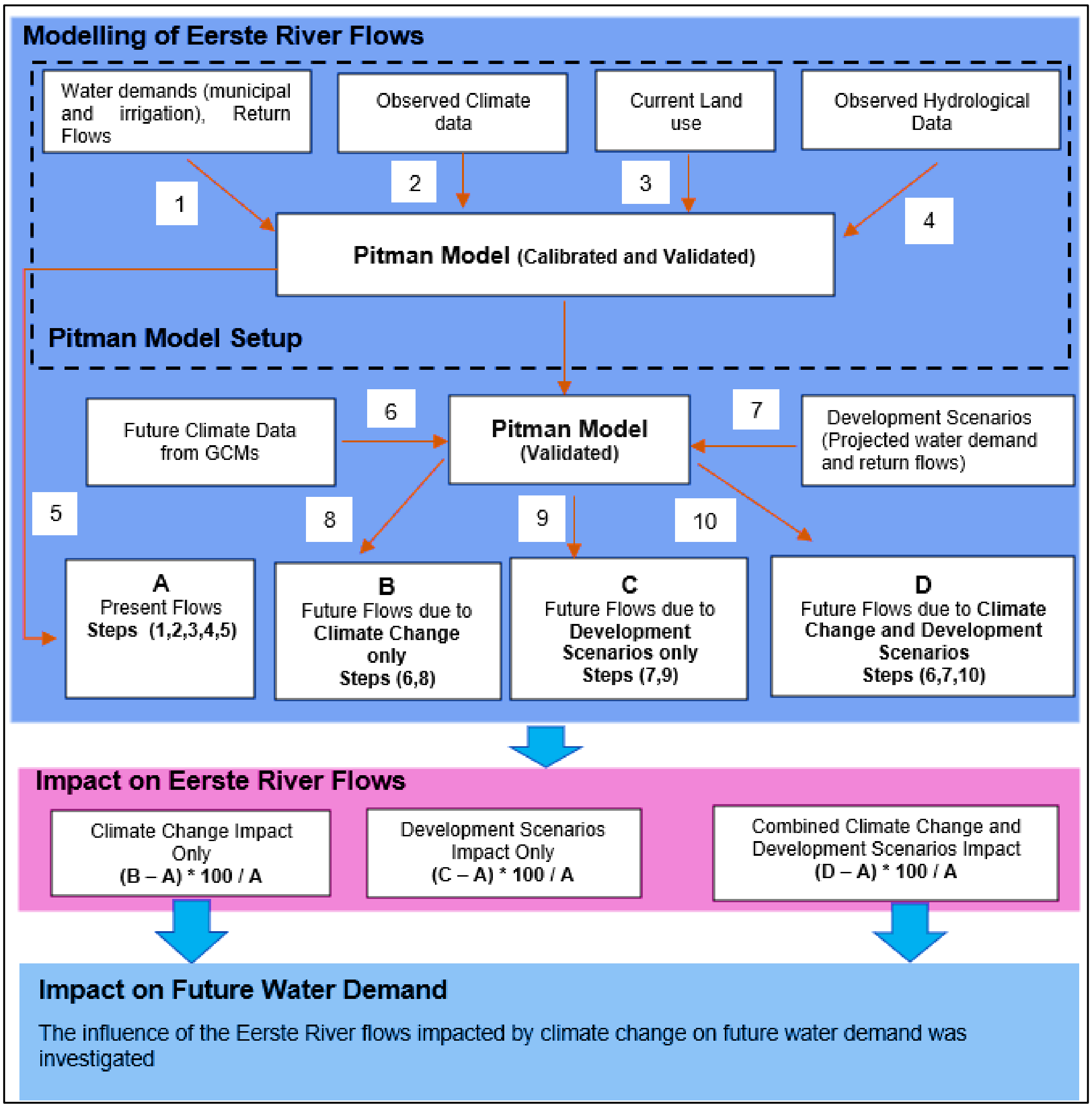

Figure 7: Framework for the Methodology of this Research

4.2 Data Collection

The data that was collected included the observed / historical stream flows, water demands (irrigation and municipal), land use/land cover map, climate data (precipitation, evaporation), Digital Elevation Model (DEM), and treated wastewater. The details of these data are presented in the following sections.

4.2.1 Streamflow

The Eerste River Catchment has four hydrological stations which are operational. These stations are used by DWS to monitor the hydrological status of the Eerste River. These stations are G2H037, G2H005, G2H020 and G2H040. The observed monthly streamflow data for these stations were retrieved from the DWS database (http://www.dwa. gov.za /Hydrology /Verified). The record period of the streamflow data, catchment areas and geographical location of the hydrological stations are presented in Table 3.

Table 3: Hydrological Stations in Eerste River

Name of the Station	Catchment Area (Km^2)	Latitude (°)	Longitude (°)	Start Date	End Date	Record Years
G2H037	24	-33.98472	18.95333	15 /06/1989	26/02/2019	30
G2H005	31	-33.97361	18.93805	01 /10/1947	26/02/2019	72
G2H020	183	-33.94980	18.83854	10/05/1978	26/02/2019	41
G2H040	328	-34.00277	18.76305	24/11/1998	12/02/2019	21

4.2.2 Climate Data

Present-Day Climate Data

The present-day climate / meteorological data for Eerste River, which were evaporation and precipitation data were retrieved from the online databases of WR2012 (https:// waterresource swr2012.co.za/) and DWS (http://www.dwa.gov.za/Hydrology/Verified). The precipitation data (1920 to 2009) that was downloaded from WR2012 database consisted of the rainfile for G2C rain zone. The G2C rain zone includes the quaternary catchments of G22F, G22G and G22H that encompasses the Eerste River Catchment. In this rainfile format, monthly rainfall was expressed as a percentage of the MAP. Precipitation data that was retrieved from DWS database was for the G2E013 rainfall station. This rainfall station is located in the Jonkershoek Mountains at geographical location -33.96388^0 and 18.92861^0 with rainfall data for the period 20/09/1968 - 01/04/2019. The rainfall data for G2E013 rainfall station was used to extend the G2C rainfile from 2009 to 2018 through regression method, which will be explained in Section 5.1.6.

The mean monthly evaporation data for G22F, G22G and G22H quaternary catchments under the 23C evaporation zone for South Africa was retrieved from WR2012 database. The “mean monthly” data was adopted because the Pitman model does not use time-varying evaporation data (Hughes *et al.*, 2013).

Future Climate Data

Future evaporation and rainfall data were determined from the total monthly precipitation, mean monthly maximum and minimum temperature data that was collected from the Climate Information Portal of CSAG (http://cip.csag.uct.ac.za /webclient2 /datasets /africa-merged-cmip5/). The collected data was generated by 11 GCMs of CMIP5 forced by RCP 4.5 and RCP 8.5 for the 1960 – 2100 period. This data was statistically downscaled to Cape Town International Airport rainfall station by CSAG, using the method explained in Hewitson & Crane (2006). The details of the 11 GCMs that were used in this research are presented in Table 4.

Table 4: List of General Circulation Models used in this Research

No	GCM	Developer	**Resolution** (Latitude x Longitude)
1	MIROC-ESM	The University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	2.8^0 x 2.8^0
2	MIROC5		1.4^0 x 1.4^0
3	MIROC-ESM-CHEM		2.8^0 x 2.8^0
4	CNRM-CM5	Centre National de Recherches Météorologiques, Centre, France	1.4^0 x 1.4^0
5	CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	2.8^0 x 2.8^0
6	FGOALS-s2	Institute of Atmospheric Physics, Chinese Academy of Sciences (LASG / IAP), China	1.7^0 x 2.8^0
7	BNU-ESM	Beijing Normal University, China	2.8^0 x 2.8^0
8	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory, USA	2.5^0 x 2.0^0
9	GFDL-ESM2M		2.5^0 x 2.0^0
10	MRI-CGCM3	Meteorological Research Institute, Japan	1.1^0 x 1.1^0
11	bcc-csm1-1	Beijing Climate Centre, China	1.1^0 x 1.1^0

4.2.3 Land Use and Land Cover

The land use and land cover (LULC) data was retrieved from WR2012 database, Wynland WUA and DEA. In this case, the LULC data that was collected from DEA was the South Africa National Land Cover-2018 denoted as SANLC 2018, which was developed from the multi-seasonal 20 m resolution Sentinel-2 satellite imagery of 2018. The SANCL 2018 data set was in the GeoTIFF raster format and was retrieved from the DEA (https://egis.environment .gov.za/gis_data_downloads). The LULC data that was collected from WR2012 database was for the 1983 – 2009 period. This data was already analysed in terms of areas of land use and land cover features of the study area. At the same time, data set collected from Wynland WUA was for 2018 irrigation features of the study area and was in GIS format.

4.2.4 Digital Elevation Model Data

The DEM that was used in this research was the global 1 Arc-Second (30 m) resolution Shuttle Radar Topography Mission (SRTM), which was developed by National Aeronautics and Space Administration (NASA) and National Geospatial-Intelligence Agency (NGA). This DEM is distributed by the United States Geological Survey (USGS) and was retrieved from the USGS Earth Explorer database (https://earthexplorer.usgs.gov/).

4.2.5 Water Demands

The water demands were defined as the water requirements for irrigation and municipal water use. In this respect, the water abstraction from Eerste River by Stellenbosch Municipality and irrigators were regarded as municipal and irrigation water demands, respectively. To properly analyse these water demands, the water demands were categorised as present-day and future as discussed below.

Present-day Water Demand

The present-day water demands were the municipal water and irrigation demands for the 1983-2018 period. The municipal water demand was in the form of water abstractions from Eerste River and was collected from WR2012 database, DWAF (2008a) and Stellenbosch Municipality for 1983-1989, 1990-2004, and 2005-2018 periods, respectively. The irrigation demand was determined in the Pitman model based on the 12 monthly crop demand factors, time-varying irrigation areas in the Eerste River Catchment and climate data which were rainfall and evaporation, retrieved from WR2012 database for the period 1983-2009. Only irrigation and rainfall data required extension up to 2018 as the remaining data was constant for the catchment. The data for irrigation areas was extended using SANLC 2018 land cover dataset, collected from DEA based on the procedure presented in Section 5.1.3.

The rainfall data from WR2012 database was extended by rainfall data collected from DWS as presented in Section 5.1.6. The data for water requirements from WCWSS to meet the irrigation demand in the catchment was collected from Wynland WUA and DWS for the 1983-2018 period. This data also included the flows diverted from the Eerste River to the irrigation canal at G2H030 monitoring station which is part of the compensation water releases from WCWSS through Kleinplaas Dam to Lower Eerste River Irrigation Board as highlighted in Section 3.1.6.

Future Water Demand

The future water demands were defined as the municipal and irrigation water demands for the 2022-2057 future period. These demands were based on the development scenarios highlighted in SM (2017a) and DWS (2014). The SM (2017a) projected the 2% and 3% per annum growth in municipal water demand of Stellenbosch Municipality for low and medium development scenarios, respectively, for the period 2014-2034. As for irrigation demand, this was based on the projection of future irrigation demand in the Eerste River Catchment in the future reconciliation scenarios projected by DWS (2014) for 2014 to 2040 period.

4.2.6 Return Flows

The return flows were defined as the treated effluent from Stellenbosch WWTW to Eerste River through the Veldwagters River. The return flows were also categorised as present-day, and future return flows. The data for the present-day return flows were collected from WR2012 database and Stellenbosch Municipality for 1983-2009 and 2009-2018 periods, respectively. As for the future return flows, the projected growth rate of future municipal water demand, as presented in Section 4.2.5, was adopted in updating the present-day return flows for 2022-2057 future period.

5. Data Analysis and Pitman Model Setup

This chapter presents the data analysis and Pitman model setup that was undertaken in this research. Data analysis is first presented, followed by the Pitman model setup.

5.1 Data Analysis

5.1.1 Streamflow

The streamflow data for G2H037, G2H005, G2H020 and G2H040 hydrological stations that were collected from DWS was analysed before it was used in the Pitman model. The analysis of this data was mainly patching of missing data using linear interpolation and converting the streamflow data into the format that is recognized in the Pitman model, which is based on FORTRAN programming language. The streamflow data for G2H040 gauging station in Fortran format for 2004 to 2009 period is presented in Appendix A.

5.1.2 Digital Elevation Model (DEM) Data

The 30 m resolution STRM DEM that was obtained from USGS for the study area was processed using ArcGIS to extract the Eerste River network and delineate the catchment of the study area. In this respect, the DEM, which was a GIS raster image, was imported into ArcGIS and was analysed using the Hydrology Tool under the Arc Toolbox. In the ArcGIS, the DEM was filled to remove the sinks which generally arise during the process of creating the DEM. The flow directions were then determined on the Filled DEM by finding the steepest slope based on the cell arrangements on the DEM. The flow accumulation process was then run on the DEM based on the flow direction of the cells to which the amount of water accumulated in the cells was determined.

The river network was then determined in ArcGIS through a process that arranges the cells on the DEM based on the amount of water accumulated in the cells. In this process, assuming the cells were in layers, it meant the cell with highest water accumulation will be on the bottom and one with the lowest water accumulation will be on top. As for the delineation of the catchment area, the mouth of the river and location of G2H040 hydrological station were located on the river network created from the DEM using the base map of South Africa to which “Snap pour Point” process in ArcGIS was run. Based on this process, the Eerste River Catchment, and the study area within the catchment, which was the area upstream of G2H040 hydrological station were then determined. In this respect, Figure 8 presents the Eerste River Catchment, the Study Area and location of hydrological stations as highlighted in Chapter 3.

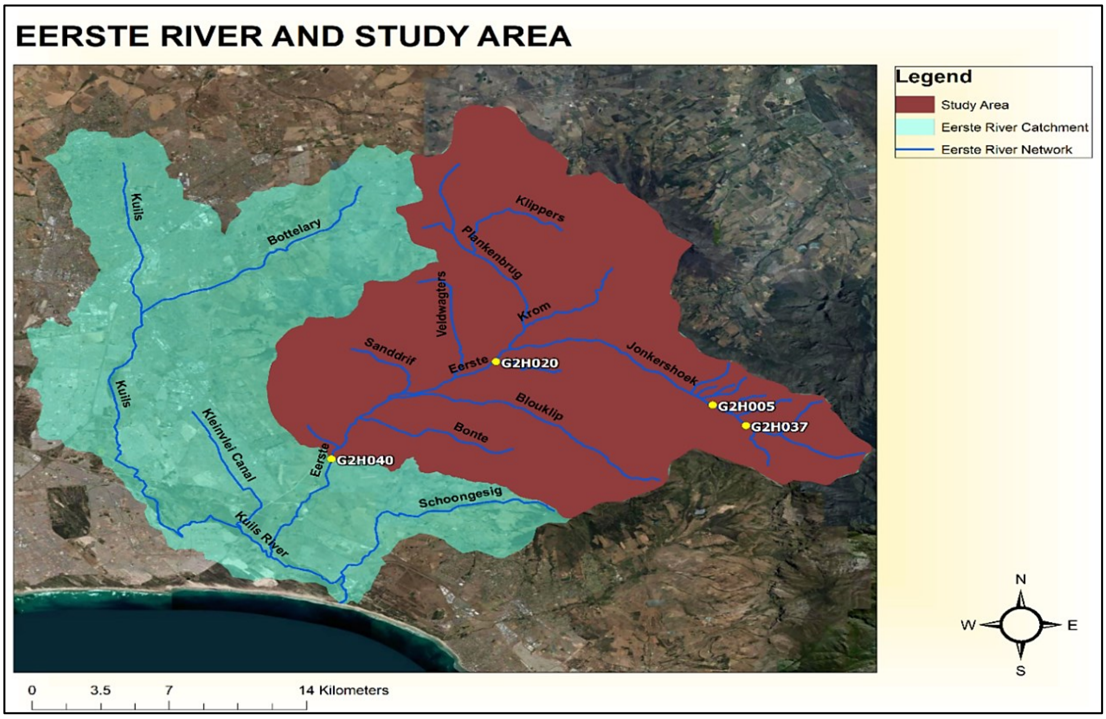

Figure 8: Eerste River and Study Area

5.1.3 Land Use and Land Cover Data

The LULC data set that was collected from WR2012 database was for the 1983-2009 period as alluded to in Section 4.2.3. The LULC dataset that was collected from Wynland WUA was for the irrigation areas and pipeline networks for the year 2018, while the one collected from DEA was SANLC 2018. The LULC data set collected from Wynland WUA and DEA was used to extend the LULC data set collected from WR2012 database from 2009 to 2018.

The Wynland WUA and SANLC 2018 data set were analysed in ArcGIS to determine the irrigation, afforestation, farm dams and alien vegetation data which was required to update the LULC data set from WR2012 database. The SANLC 2018 dataset was a raster image for the LULC of the whole of South Africa. The SANLC 2018 data set was first clipped to the study area in the ArcGIS and then converted to polygon format using Data Management Tools under the ArcToolbox. The required LULC, like farm dams and their properties, e.g. area of farm dams, were determined by using the class features of the SANLC 2018, and the selection and statistics tools of the ArcGIS, respectively. Figure 9 presents the analysed SANLC 2018 dataset.

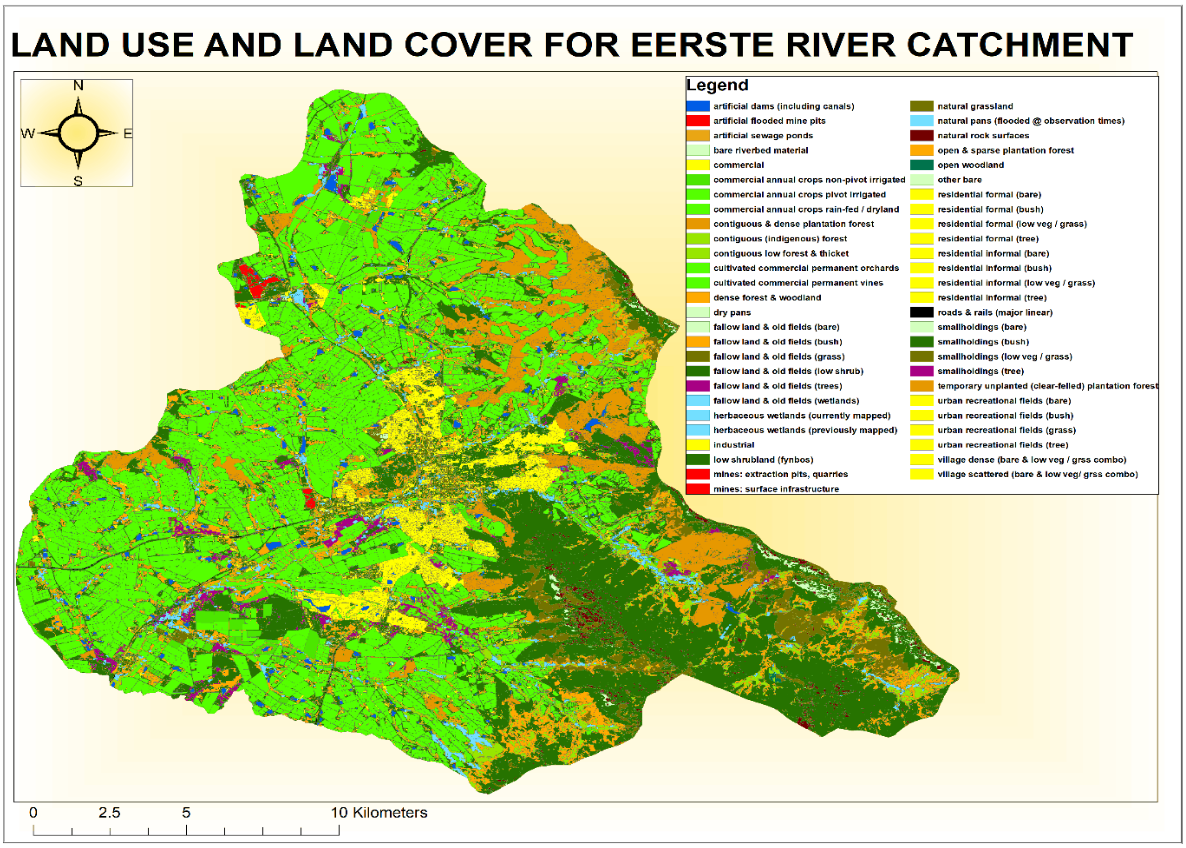

Figure 9: Land Use and Land Cover for Eerste River Catchment

Based on the above procedure, Figure 10 presents the location of the irrigated agricultural land use in the study area and its corresponding area in km^2 as determined in ArcGIS. The area of irrigated agriculture in the study area was determined to be 118.8 km^{2,} as presented in Figure 10.

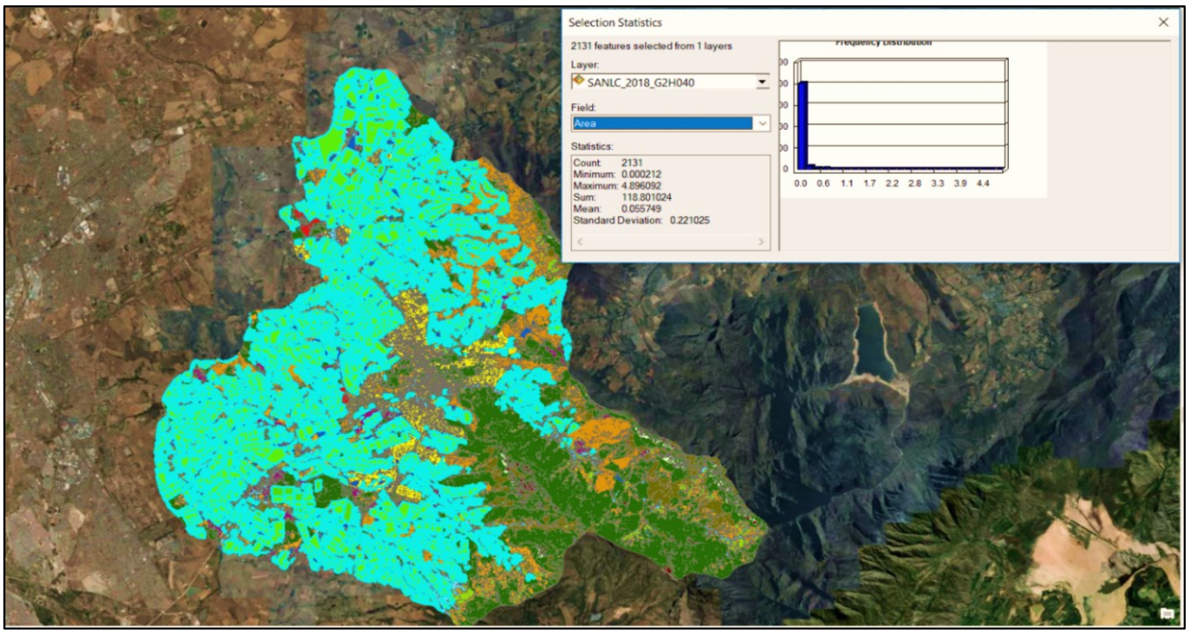

Figure 10: Location of Irrigated Agriculture Land Use in the Study Area

The area for afforestation (commercial pine trees), alien vegetation (eucalyptus and black wattle), farm dams, and irrigated agriculture LULC as of the year 2018 were determined using the procedure as highlighted above.

The Wynland WUA LULC for 2018 was a GIS map that had details of the source of water that was allocated to the farms within the irrigation boards as part of the information in the metadata. The Wynland WUA LULC was then used to assist in identifying the farms that utilised direct water distributed through pipelines from WCWSS. To access this information, the Wynland WUA LULC was first clipped on the LULC of the study area (Figure 9) in ArcGIS. The clipped Wynland WUA LULC was then exported to Google Earth in kml format to which farms that had access to water distributed through pipelines from WCWSS within the irrigation boards were identified. The irrigation areas of the identified farms were then read off from the metadata. Figure 11 presents the clipped Wynland WUA LULC showing the irrigation boards and pipeline network within the study area.

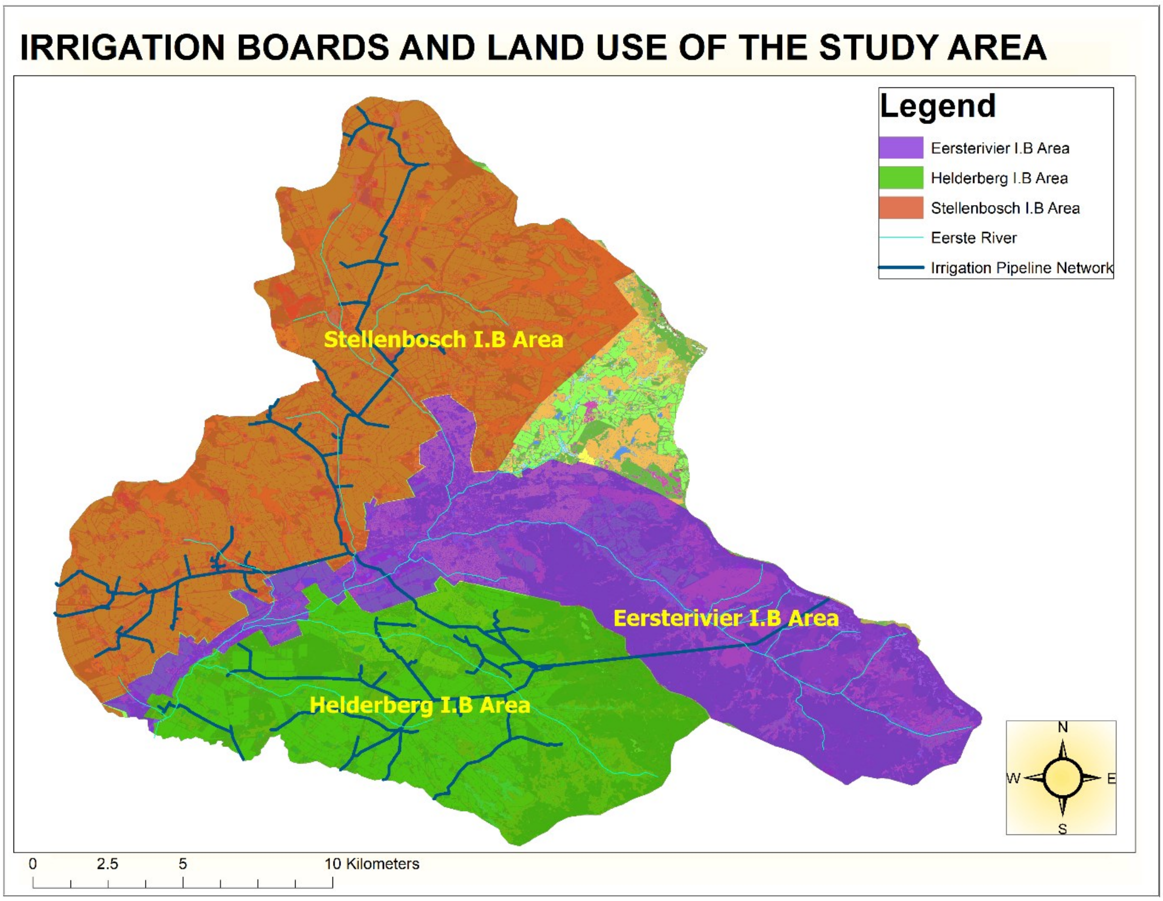

Figure 11: Irrigation Boards and Land Use of the Study Area

5.1.4 Water Demands and Development Scenarios

Present-day Water Demand

The present-day municipal water demand was composed of the data from WR2012 database, DWAF (2008a), and Stellenbosch Municipality for 1983-1989, 1990-2004 and 2005-2018 periods, respectively. As for the present-day irrigation water demand, the 12 monthly crop demand factors and climate data for the Eerste River Catchment together with the time-varying irrigation areas were utilised in the Pitman model to determine the demand.

Three sources of water were considered in the Pitman model to meet the irrigation demand. These sources were Farm dams (direct rainfall), Eerste River (together with compensation water releases from WCWSS), and WCWSS using pipelines as highlighted in Section 3.1.6. Table 5 presents the source of water for irrigation use that were considered in this research with respect to Wynland WUA.

Table 5: Source of Water for Irrigation Use in Wynland WUA

Name of the Irrigation Board	**WCWSS**	**Farm Dams** (Based on direct rainfall and dam capacity)	**Eerste River** (Based on catchment runoff and baseflow)
Helderberg	yes	yes	yes
Stellenbosch	yes	yes	yes
Lower Eerste River	yes (compensation water releases from Kleinplaas Dam to Eerste River)	yes	yes

The annual water requirements to Helderberg and Stellenbosch Irrigation Boards from WCWSS were determined by multiplying the irrigation areas that utilised water distributed by pipelines from WCWSS, with a capped water allocation of 4000 m^3/ha/a. These irrigation areas were determined by the procedure that has been highlighted in Section 5.1.3. The monthly time series of these annual water requirements were then determined using the distribution pattern or percentages presented in Table 2 for the period 1992-2018. The 1992-2018 period was adopted because it was the period that the water from WCWSS distributed by the pipelines had been in existence as highlighted in Section 3.1.6.

The water requirements for the compensation water releases to Lower Eerste River Irrigation Board from the WCWSS through Kleinplaas Dam were determined differently to the water requirements in Helderberg and Stellenbosch Irrigation Boards as highlighted above.

The water requirements for the compensation water releases were part of the flows observed at G2H005 which was located downstream of the Kleinplaas Dam. This notion was adopted because G2H005 measures the spillage and compensation water releases from Kleinplaas Dam to Eerste River as well as incremental flows from the catchment area between the dam and the gauging station which was deemed to be 1 km^2. There was no data that could be used to establish a long-term monthly pattern of the compensation water releases from the Kleinplaas Dam.

The water requirements were then determined by subtracting the spillage flows of the Kleinplaas Dam from the observed flows at G2H005 for the 1983-2018 period. These spillage flows were denoted as G2R001 and were retrieved from the DWS database similarly to the way it was done for the observed flows at the G2H005. The 1983-2018 period was adopted because these water requirements started to be released from the Kleinplaas Dam to Eerste River in 1982, which is the year the dam was constructed as highlighted in Section 3.1.6.

By using the above procedure, the determined compensation flow releases also included the incremental flow from the catchment area between the Kleinplaas Dam and the gauging station. The incremental flows from the catchment were considered insignificant to influence the compensation water releases based on the size of the catchment area. For the sake of representing the actual water resources in the Eerste River catchment downstream of G2H005, the compensation water releases were still considered to have included the incremental flows. The configuration of the compensation water releases with the incremental flows from the catchment, and the spillage from the Kleinplaas Dam (G2R001) in Pitman Model is presented in Figure 18 under Section 5.2.2. The configuration of water requirements from WCWSS in the Pitman model, as highlighted above, was based on the procedure explained in Section 5.2.9.

Future Water Demand

The future water demand was based on the projection of the present-day municipal and irrigation water use in the future. In this respect, the future water demand was determined based on the modelling of the impact of climate change only, development scenarios only, and combined climate change and development scenarios.

The future municipal and irrigation water demand for the assessment of the impact of climate change only on Eerste River was determined to be the municipal and irrigation water demand of the present-day period, which was from 1983 to 2018. In this case, it was assumed that there is no change in the irrigation area that could result in the change of irrigation demand.

At the same time, there would be no change in municipal water demand through an increase in population or social-economic activities in the 2022-2057 and 2058-2093 future periods relative to the present-day period. This approach was adopted because it presented a situation that allowed independent analysis of the impact of climate change on Eerste River flow because the present-day status of the land cover and water demand was considered to be constant, and only the climate data from GCMs were varying in the future periods.

As for the modelling of the impact of development scenarios only on Eerste River, the future water demand was for 2022-2057 period only and was determined based on growth rates of municipal water demand reported in SM (2017a) and the present-day irrigation water demand. The municipal water demand in Stellenbosch Municipality was projected to grow at 2% and 3% per annum for low and medium water requirements scenarios for the period 2014-2034 based on SM (2017a) as highlighted in Section 2.3.2. These growth rates of municipal water demand were adopted in this research based on the understanding that the municipal water that was being assessed was the water abstracted by the Stellenbosch Municipality from Eerste River. It was deemed that these growth rates were more applicable to the study area.

As for the future water demand for irrigation, this was determined based on the projected water requirements from WCWSS and own sources (farm dams and run-of-river). For the demand from the WCWSS, this research adopted the projections reported in DWAF (2007b) and DWS (2014) that showed that the water requirements for irrigation in WCWSS would grow at a constant rate of 2% per annum in both high and low water requirement scenarios for 2006-2030 and 2013-2040 periods, respectively until the capped water allocations are attained.

It was noted from the data collected from Wynland WUA that DWS allocated 4000 m^3/ha/a in Wynland WUA in the 2009-2016 period, which is the capping limit for water allocation for this WUA as highlighted in Section 3.1.6. Therefore, it meant that in Wynland WUA, the capped water allocation from WCWSS had already been attained as projected in DWS (2014). It was then considered that 2% growth rate for the future water requirements for irrigation from WCWSS to Wynland WUA was no longer applicable.

As for the growth rate for future water requirements from other own sources like farm dams and run of river, the growth rate was not known as highlighted in Section 2.3.3 of Chapter 2. It was then assumed that future water requirements from WCWSS would be varying based on the water allocations by DWS like in the present-day period. The farmers that have access to water from the WCWSS would use their water allocations either below or equal to the capped limit of 4000m^3/ha/a. As for the other farmers that do not have access to water from WCWSS, their present-day water requirements for irrigation would be maintained as the future demand.

In this research, two development scenarios were adopted for future irrigation and municipal water demands for modelling of the impact of development scenarios on Eerste River. These scenarios were denoted as Low and High Development Scenarios. In the Low Development Scenario, municipal water demand was expected to grow at a rate of 2% per annum as projected in SM (2017a). As for irrigation, future demand was deemed to be the same as for the present-day period with water requirements from WCWSS capped at 4000m^3/ha/a. For the High Development Scenario, the municipal water demand was anticipated to grow at a rate of 3% per annum, as presented in SM (2017a). For irrigation, the present-day water demand and water requirements from WCWSS capped at 4000m^3/ha/a were maintained. Table 6 presents the adopted future projections for irrigation and municipal water demand for Low and High Development Scenarios for the 2022-2057 period.

Table 6: Water Demands Projection and Development Scenarios

Water Use	Low Development Scenario	High Development Scenario
Municipal	2%	3%
Irrigation	same as the present-day period	same as the present-day period

The long term average (LTA) of municipal water demand for the recent past period (2009-2018) was assumed to be that of the year 2022, and this water demand was projected up to the year 2057, using the growth rates as highlighted in Table 6. The average of the municipal water demand for the recent past period was adopted because it was assumed to be more representative as it was not far from the year 2022. The adopted procedure is illustrated in Table 7 using the High Development Scenario, and long term average of municipal water demand in million cubic meters (Mm^3) for the 2009-2018 period.

Table 7: Projection of Future Municipal Water Demand (in million m^3 / month)

LTA (2009 - 2018)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
	0.44	0.44	0.44	0.46	0.43	0.42	0.31	0.29	0.31	0.38	0.36	0.39
Year	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**
2022	0.44	0.44	0.44	0.46	0.43	0.42	0.31	0.29	0.31	0.38	0.36	0.39
	0.44 *1.03											
2023	0.45	0.45	0.45	0.47	0.44	0.43	0.32	0.30	0.32	0.39	0.37	0.40
	0.46 *1.03											
2024	0.47	0.47	0.47	0.49	0.46	0.45	0.33	0.31	0.33	0.40	0.38	0.41

Future irrigation demand in the Low and High Development Scenarios was determined in the Pitman model based on the irrigation areas of the year 2018 which were maintained for the 2022-2057 period, the 12 monthly crop demand factors and climate data. As for the water requirements from the WCWSS, these were determined using the same procedure adopted for the irrigation water requirements of the present-day period as highlighted above. In the modelling of the combined impact of climate change and development scenarios, the future municipal water and irrigation demand in the Eerste River Catchment was based on the demand adopted in the modelling of the impact of development scenarios on Eerste River as presented above.

5.1.5 Return Flows

The return flows were the treated wastewater flows to Eerste River from Stellenbosch WWTW as highlighted in Section 4.2.6. These return flows were analysed using the same approach adopted for municipal water demand in Section 5.1.4 for modelling of the impact of both climate change and development scenarios on Eerste River. The return flows for the present-day period was the data that was collected from WR2012 database and Stellenbosch Municipality for 1983-2009 and 2009-2018 periods, respectively. There were gaps in the return flows data for the 2009-2018 period, which were patched by using the long term average of each specific month.

The return flows for the present-day period were adopted as the return flows for 2022-2057 and 2058-2093 future periods in the modelling of the impact of climate change only. The modelling of the impact of development scenarios only, the return flows for the year 2022 were then projected up to the year 2057 based on the growth factors of the low and high development scenarios for municipal water demand as presented in Table 6. The approach illustrated in Table 7 was also adopted to determine the return flows for 2022-2057 period. The growth rates for municipal water demand were adopted for return flows because it was assumed that the pattern of the amount of wastewater is directly proportional to the amount of municipal water in the water supply network.

The projection of the return flows due to development scenarios was also based on a weighted ratio of linear contribution of the municipal water to the Stellenbosch WWTW based on the source of treated municipal water. This approach was adopted because the water supply network of Stellenbosch Municipality has two sources of raw water. These sources are Eerste River and WCWSS to which abstracted water is treated at Idas Valley Water Treatment Works and Paradyskloof Water Treatment Works (WTW), respectively, with a treatment capacity of 28 Ml/day and 10 Ml/day, respectively. In this way, the increase in wastewater to Stellenbosch WWTW was because of the corresponding increase of municipal abstractions in Eerste River to Idas Valley WTW and not from WCWSS through Paradyskloof WTW.

The weighted ratio that was adopted was 0.73 (28 Ml/day / 38 Ml/day) which was the minimum expected contribution of wastewater to the Stellenbosch WWTW in the municipality from the water treated at Idas Valley WTW. The term “minimum” was adopted because the treatment capacity of Idas Valley WTW could increase in the future relative to the treatment capacity of Paradyskloof WTW as a corresponding response to the increase in municipal water abstractions. In this way, the return flows contributed from raw water sourced from WCWSS was assumed to be constant in the near-future period. This approach also assumed that the percentage of treated municipal water being converted to sewer or wastewater at a household or institution level is the same regardless of the WTW supplying water to the water supply network. In other words, the contribution of wastewater to Stellenbosch WWTW will depend on the percentage of water to the water supply network from the WTW.

As for modelling the combined impact of climate change and development scenarios, the future return flows for modelling the impact of development scenarios were adopted.

5.1.6 Climate Data

Present-Day Climate Data

The present-day climate data were precipitation (for the G2C rainfall zone) and evaporation (for the 23C evaporation zone) collected from WR2012 and DWS databases. The Pitman model only accepts the long-term averages of monthly evaporation, and the data collected from WR2012 was already available in this format.

The precipitation data in the G2C rainfile, from WR2012 database, covered the 1983-2009 period. There was a need to extend the G2C rainfile data from 2009 to 2018 because the present-day period was accepted as 1983-2018. The rainfall data for G2E013 rainfall station, which was collected from DWS, covering the period 1960-2018, was used for extension of the rainfall data. The Regression method was adopted for the extension of the rainfall data with a significant coefficient of determination between these two rainfall data sets, as presented in Figure 12.

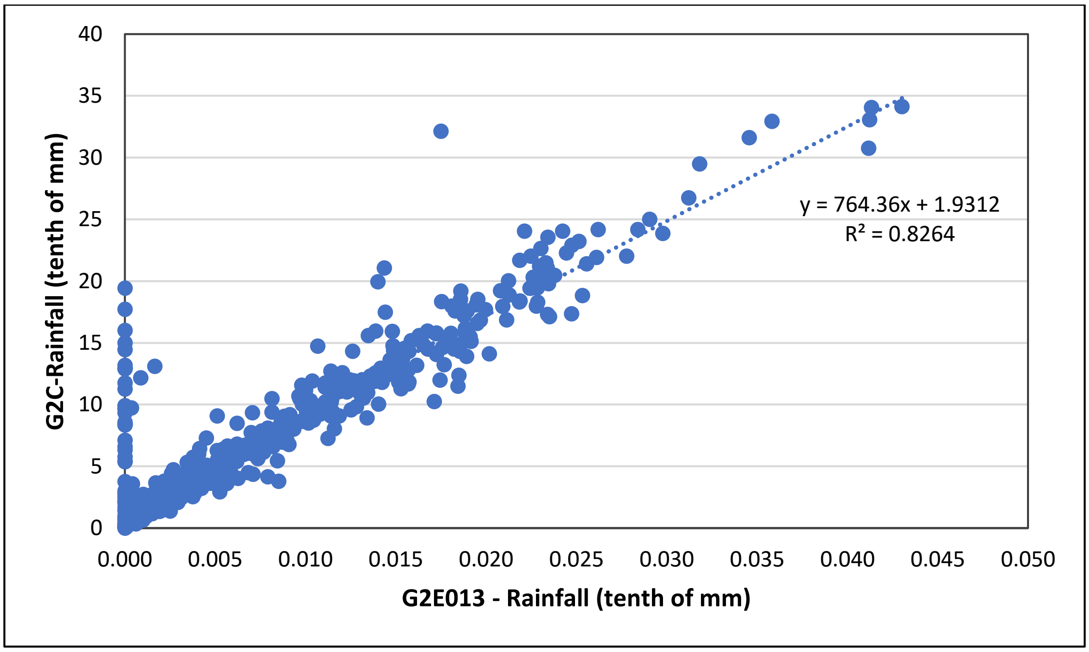

Figure 12: G2E013 - G2C Rainfile Rainfall

The regression equation presented in Figure 12 was then used to extend the rainfall data. In the Pitman model, the rainfall for G22F, G22G and G22H quaternary catchments, which covered the Eerste River, was determined by multiplying the extended G2C rainfile with the MAP of the quaternary catchments. The MAP for the G22G and G22H quaternary catchments were 785 mm and 815 mm, respectively, based on the rainfall data collected from WR2012 database.

As for G22F quaternary catchment, there were two MAP values, 1629 mm and 785 mm, which were for the areas above and below the Kleinplaas Dam, respectively. DWAF (2008a) reported that the MAP values in G22F quaternary catchment for the area above and below the Kleinplaas Dam were 1900 mm and 1310 mm, respectively. The adopted MAP values for the area above and below Kleinplaas Dam in this research were 1629 mm and 1310 mm, respectively, based on the calibration of the Pitman model, which is explained in Section 5.2.3. The location of G22F, G22G and G22H quaternary catchments, G2C Rainfall Zone and G2E013 rainfall station in respect to the study area is presented in Figure 13.

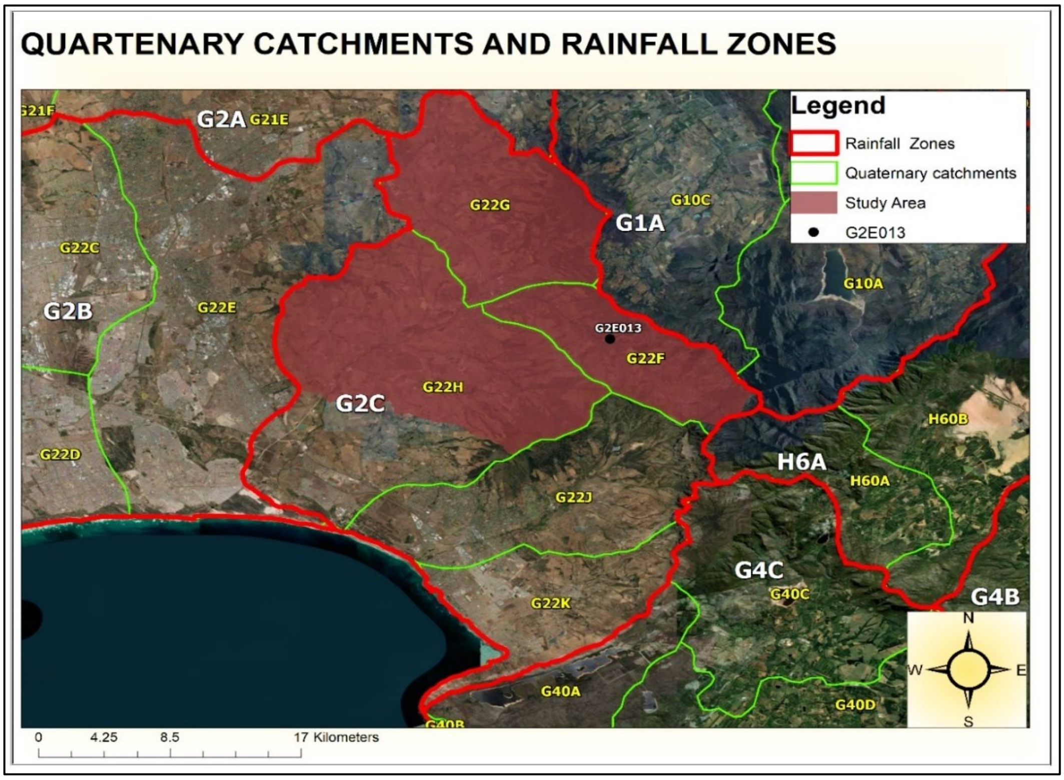

Figure 13: Location of Quaternary Catchments and G2C Rainfall Zone

Future Climate Data

The future climate data that was collected from the CSAG was the total monthly precipitation, mean maximum and minimum temperature data for 1960-2100 period, which was generated by 11 GCMs as highlighted in Section 4.2.2. The data for the 2022-2057 and 2058-2093 future periods was used to determine the climate change signal, which was required to be transferred to observed climate data of the present-day period or the baseline period. The general overview of the procedure that was adopted to analyse the future climate data is expressed in Figure 14.

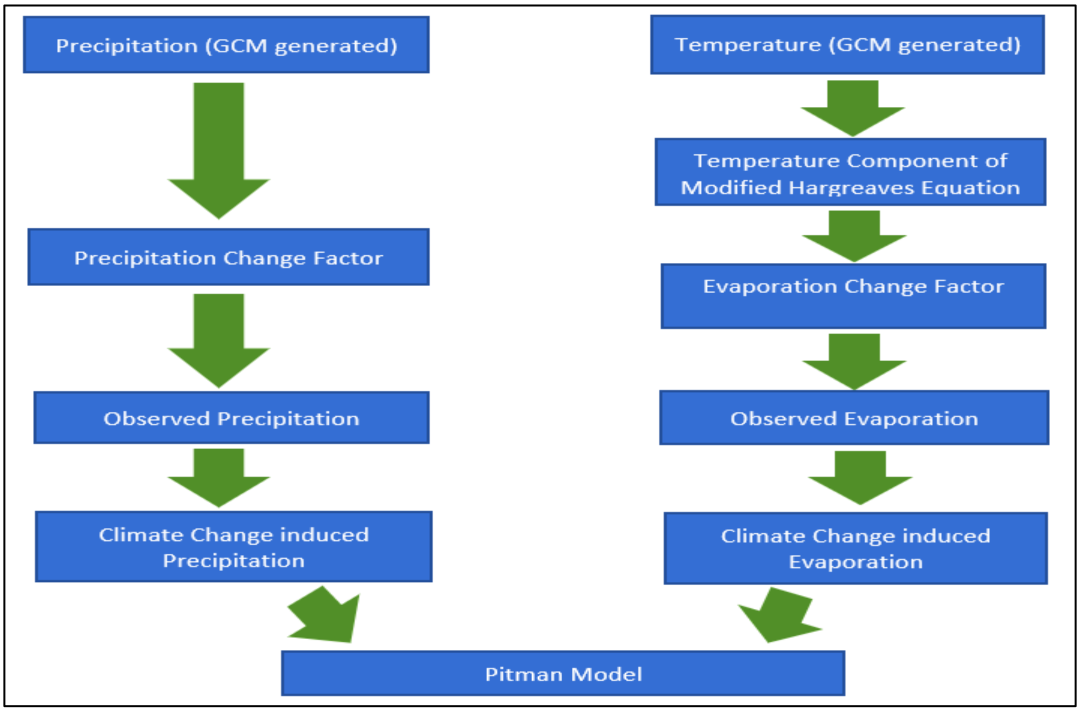

Figure 14: Procedure for Analysing Future Climate Data

The climate change signal from the future precipitation data, as presented in Figure 14, was determined using the change factor for precipitation calculated with Equation 4. This procedure is illustrated in Table 8 using mean monthly precipitation generated by MIROC GCM under the influence of RCP 8.5 for the 1983-2018 and 2022-2057 periods, which were present-day / baseline and near-future period, respectively.

Table 8: Calculation of Climate Change Signal

Month	GCM-Baseline Precipitation (mm) (1)	GCM-Future Precipitation (mm) (2)	Climate Change Signal (3) = (2) / (1)
October	89.18	98.25	1.10
November	59.74	63.24	1.06
December	48.45	34.80	0.72
January	21.29	21.14	0.99
February	14.21	15.36	1.08
March	24.16	23.51	0.97
April	45.69	48.46	1.06
May	86.28	99.37	1.15
June	94.81	88.94	0.94
July	109.08	100.59	0.92
August	113.99	113.90	1.00
September	97.72	99.24	1.02

The climate change signal of each GCM was determined based on the procedure presented in Table 8. The climate change signal for the ensemble mean of 11 GCMs adopted in this research was determined as the average of the climate change signal of the 11 GCMs. The climate change-induced or future precipitation for the 2022-2057 and 2058-2093 periods was then determined by applying the climate change signal of the ensemble mean of the 11 GCMs to the observed precipitation for the present-day period, which was the extended G2C rainfile, using Equation 6.

The procedure of determining the future precipitation for the year 2057 is illustrated in Table 9 using observed rainfall for the year 2018 of the G2C rainfile and climate change signal for the ensemble mean of GCMs induced by RCP 8.5. Precipitation in Table 9 is in the percentage of MAP, which was the format for the rainfall data of the G2C rainfile.

Table 9: Calculation of Future Precipitation

Month	Climate Change Signal (1)	Observed Precipitation - 2018 (% of MAP) (2)	Future Precipitation - 2057 (% of MAP) (3) = (2) * (1)
October	0.97	6.73	6.53
November	0.99	5.99	5.93
December	0.93	3.11	2.89
January	1.09	2.11	2.30
February	0.98	2.65	2.60
March	1.00	3.37	3.37
April	0.97	8.57	8.31
May	1.03	12.28	12.65
June	0.92	18.02	16.58
July	0.97	9.75	9.46
August	0.97	12.58	12.20
September	1.02	10.62	10.83

The temperature data generated by the GCMs were analysed using the modified Hargreaves Equation (Equation 8), for the determination of the temperature component that was used to calculate evaporation. The climate change signal for evaporation was then determined using Equation 9, based on the results from Equation 8 for the baseline / present-day and future periods. The calculation of the climate change signal for evaporation using Equation 9 is similar to using Equation 4 for climate change signal for precipitation in Table 8. The climate change signal of the ensemble mean of 11 GCMs was then transferred to the observed evaporation data from WR2012 database using Equation 6 for determination of climate change-induced evaporation similarly to the way it was done for precipitation in Table 9.

The calculation of the temperature component of the Hargreaves Equation, which was used to determine the evaporation is illustrated in Table 10 based on Equation 8. The data used in the calculation is mean monthly maximum and minimum temperature generated by FGOALS-s2 GCM induced by RCP 8.5 for the year 2059.

Table 10: Calculation of Temperature Component of Hargreaves Equation

Month	Mean Minimum Temperature (^{0}) (1)	Mean Maximum Temperature (^{0}) (2)	Temperature Component of Hargreaves Equation (3) = [(2) + (1)] / 2 * [(2) – (1)]^0.5
October	13.81	23.50	58.07
November	13.91	23.35	57.24
December	18.02	27.77	71.49
January	19.26	29.22	76.50
February	19.56	29.38	76.68
March	19.27	30.83	85.17
April	19.02	29.28	77.36
May	17.35	26.94	68.58
June	12.60	22.35	54.57
July	11.83	22.56	56.33
August	12.30	24.12	62.61
September	13.27	22.73	55.36

This research adopted the use of change factors or transferring of the climate change signal to the baseline / present-day precipitation and evaporation data to minimise transferring of the GCM biases to the climate input data in the Pitman model as recommended by Johnson & Sharma (2015).

Most of the times, the GCMs outputs of the baseline scenario, when compared to historical climate data of the present-day period, do not synchronise, especially in the pattern of the seasonal or long-term trend. The use of this approach inherited the assumption that the future climate variability will be the same as of the present-day climate as reported by WIDER (2016). This approach was still adopted so that the absolute change of future climate could be analysed in the Pitman model relative to the present-day climate.

The climate change signal, as presented above, was determined using the climate data downscaled at the Cape Town International Airport rainfall station. The climate change signal was deemed to be the same as that of Eerste River Catchment given the proximity of these areas. Both areas fall in the same evaporation zone.

Besides, the precipitation pattern is the same for both rain zones of Cape Town International Airport area (G2B), and Eerste River Catchment (G2C). This notion emanated from the understanding that these rain zones are influenced by the same circulation systems of climate as reported by Du Plessis & Scholms (2017) and Ching'ombe (2012). Figure 15 presents the location of the Cape Town International Airport rainfall station and study area relative to the evaporation and rain zones. The rainfall station has been renamed "Cape Town" instead of "Cape Town International Airport" for the sake of clarity of the features in Figure 15.

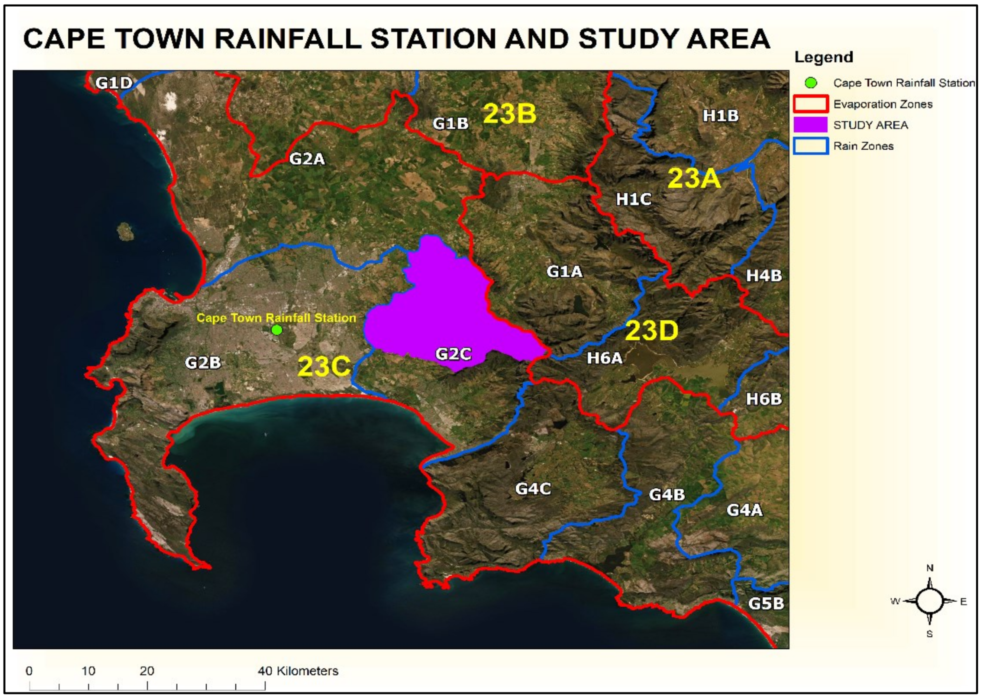

Figure 15: Cape Town International Airport Rainfall Station and Study Area

The climate change signal was determined based on the ensemble of the 11 GCMs outputs as a way of minimizing the uncertainty that arises due to use of single GCM outputs (Qian *et al.*, 2016). IPCC recommended this approach in undertaking the climate change impact studies because the use of multiple GCMs provides a general understanding of the direction and relative magnitude of change of future climate than the use of single GCM, which only provide one scenario of the future climate change (Setegn *et al.*, 2011). Therefore, the scale of confidence in assessing the uncertainty recommended by IPCC, presented in Table 1, was modified and adopted in this research, as presented in Table 11.

Table 11: Modified Scale of Confidence for Uncertainty of GCMs

Confidence Terminology	Degree of Confidence
Very high confidence	At least 10 out 11
High confidence	About 9 out of 11
Medium confidence	About 6 out of 11
Low confidence	About 3 out of 11
Very low confidence	Less than 2 out of 11

Table 11 presents that if at least 9 of 11 GCMs projected the same direction of change, then it meant that there was high confidence that the projections of the climate would tend to follow that direction.

5.2 Pitman Model Setup

5.2.1 Modelling Procedure in Pitman Model

In this research, the Pitman model version 2.11 (WRSM2000) was adopted as the hydrological model for the simulation of the Eerste River. The model used monthly data of rainfall and evaporation, time-varying land use data, water demand (irrigation and municipal), and groundwater information (aquifer characteristics) to simulate the stream flows. The simulated stream flows were compared to observed stream flows based on the modelling objectives, i.e. determining the changes in streamflow or calibrating and validating of the model.

The Pitman model used a network of four modules linked by routes to simulate the stream flows of the catchment. These modules were Runoff Module (RU), Channel Reach Module (CR), Reservoir Module (RV), and Irrigation Module (RR). The RU module simulated the runoff generated from the catchment in the model. This module was where land use data of the catchment, i.e. afforestation and climate data (rainfall and evaporation) were represented.

The afforestation and alien vegetation areas in the RU module were regarded as streamflow reduction areas of the catchment because these types of vegetation are considered to have a higher affinity of water than the indigenous natural vegetation. The CR module was used to collect and distribute water flows to other modules through routes which were conduits of the flows. As for the RV and RR modules, these were used to represent the dams or farm dams and the irrigation water requirements in the catchment, respectively.

The observed stream flows were assigned to the gauging stations, which were located on the routes while the water abstractions and return flows (treated wastewater) were connected to the CR Module. Figure 16 presents a typical sub-catchment network that is used in the Pitman model as a way of illustrating the sub-catchment network.

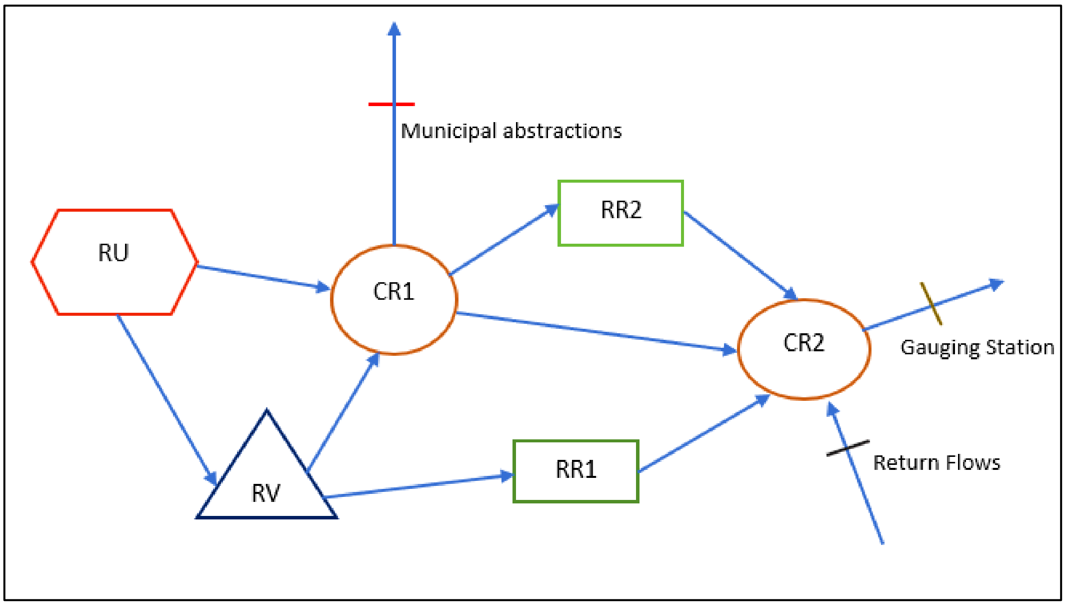

Figure 16: Typical Sub-Catchment Network in Pitman Model

Figure 16 presents that the RU module generates the flow in the catchment, which is distributed to the farm dams (RV) and channel reach module (CR1). The water from the farm dam is distributed to the CR1 and irrigated area (RR1). The water from CR1 is abstracted for municipal water use and then distributed through the river to irrigated area RR2 and channel reach module CR2. The remaining water from the upper catchment area is supplemented with return flow (treated wastewater) and then measured at the gauging station located at the end of the sub-catchment.

The Eerste River Catchment was modelled by dividing the catchment into smaller sub-catchments based on the location of flow gauging stations, as illustrated in Figure 16. These sub-catchments were inter-connected in the model. This approach of using sub-catchments was adopted because it provided an opportunity to assess or validate the model performance through comparison of the simulated and observed stream flows at the gauging station of each sub-catchment as recommended by Bailey & Pitman (2016).

The stream flows were modelled incrementally from upper to lower sub-catchments, such that the cumulative stream flows of the whole catchment were those that were observed at the last gauging station of the Eerste River Catchment. The configuration of the Eerste River catchment in the Pitman model is presented in the next section.

5.2.2 Configuration of the Eerste River Catchment in Pitman Model

The Eerste River was modelled using the procedure highlighted in Section 5.2.1 to which the Eerste River Catchment was divided into five sub-catchments based on the exiting gauging stations and quaternary catchments. These sub-catchments were G2H005-G22F, G2H020-G22F, G2H020-G22H, G2H020-G22G and G2H040-G22H. The name of the sub-catchment was made up of the names of the gauging station and quaternary catchment. The gauging station is where the river flows are measured in the sub-catchment, and the quaternary catchment is where the sub-catchment is located.

For example, the naming of G2H020-G22G sub-catchment meant that flows in the sub-catchment are measured at G2H020 gauging station and that the sub-catchment lies in G22G quaternary catchment. This naming style was adopted to assign the correct MAP value to the sub-catchments as it has been highlighted in Section 5.1.6 that Eerste River has varying MAPs which depends on the quaternary catchments. Figure 17 presents the location of these sub-catchments in the Eerste River Catchment with regard to the gauging stations and quaternary catchments.

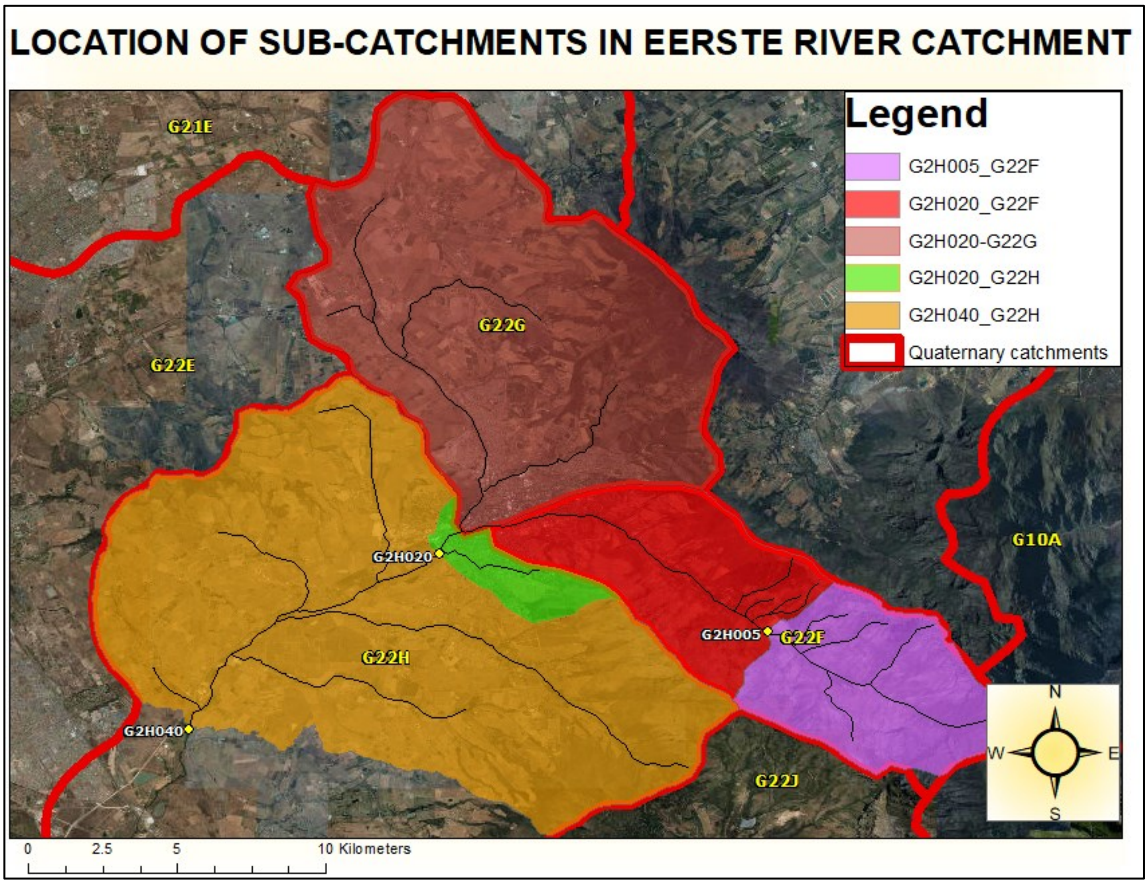

Figure 17: Location of Sub-Catchments in Eerste River Catchment

Figure 17 presents that the stream flows simulated in the G2H005-G22F sub-catchment were compared with the observed streamflow at G2H005. After G2H005, the next gauging station is G2H020. The area between G2H005 and G2H020 lies in three quaternary catchments which are G22F, G22G and G22H. Three sub-catchments were demarcated based on the quaternary catchments so that the streamflow generated from each quaternary catchment could be appropriately quantified using the specific quaternary catchment MAP values.

This area was split into three sub-catchments which were G2H020-G22F, G2H020-G22G, and G2H020-G22H which represented the areas within G22F, G22G and G22H quaternary catchments, respectively. After G2H020 the next gauging station is G2H040, and the area in between these two gauging stations lies in G22H quaternary catchment. One sub-catchment was assigned for this area which was named G2H040-G22H.

Based on the above locations of the sub-catchments, the configuration of the sub-catchments in the Pitman model was in such a way as to mimic the water resources distribution in the Eerste River Catchment. The schematic layout of the water resources distribution in Eerste River Catchment is presented in Appendix B. The configuration of the sub-catchments in the Pitman model based on the schematic layout in Appendix B is presented in Figure 18.

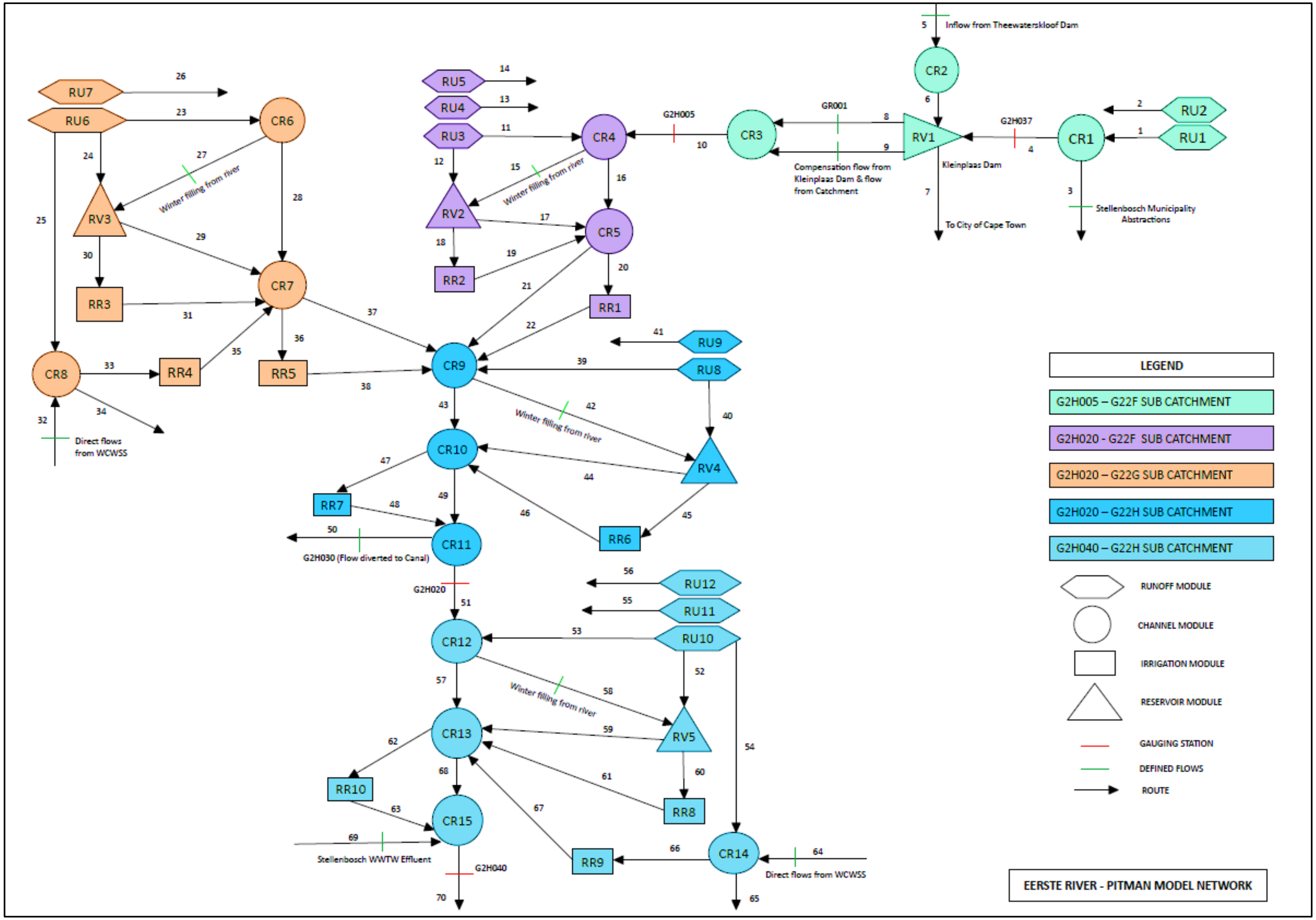

Figure 18: Configuration of the Sub-Catchments in the Pitman Mode

The flows at G2H037 and G2H005 were analysed based on flows from G2H005-G22F sub-catchment while flows at G2H020 were based on accumulated flows from G2H020-G22F, G2H020-G22G, and G2H020-G22H sub-catchments as well as accumulated flows from G2H005. The flows at G2H040 were based on the incremental flows from G2H040-G22H sub-catchment and the accumulated flows from G2H020. The configuration of the Eerste River, as presented in Figure 18, is described in the following section.

G2H005-G22F Sub-Catchment

The G2H005-G22F sub-catchment was configured in the Pitman model, as presented in Figure 19.

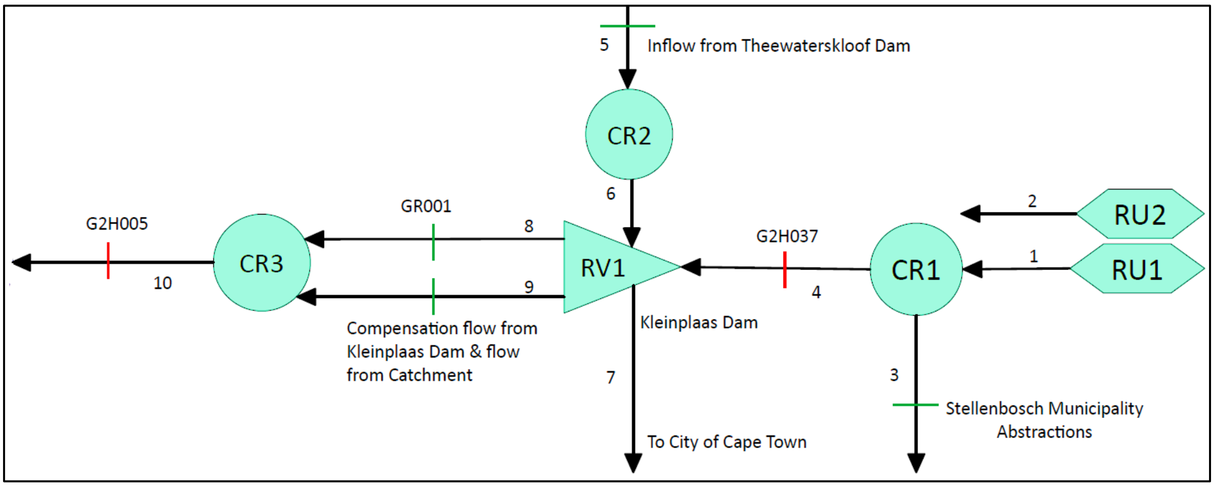

Figure 19: Configuration of G2H005-G22F Sub-Catchment in the Pitman Model

Figure 19 highlights that the upper catchment of the Eerste River, which was represented by RU1 runoff module was generating naturalised flows. These naturalised flows were denaturalised by the afforestation area represented by RU2 runoff module. The denaturalised flows were then abstracted by the Stellenbosch Municipality for municipal use to which the remaining water was then measured at G2H037 before flowing into the Kleinplaas Dam.

At the Kleinplaas Dam, the flows from Eerste River were supplemented by the water from WCWSS through the Riviersonderend inter-basin water transfer scheme represented by routes 5 and 6. The compensation water releases and incremental catchment flow together with the spills (GR001) represented by routes 9 and 8, respectively, were then measured at the downstream gauging station G2H005. The diverted water to the City of Cape Town through Stellenboschberg Tunnel as presented in Appendix B was represented by route 7.

The water from WCWSS was only considered for the modelling of the compensation water releases from the Kleinplaas Dam. Thus, the modelling did not simulate the actual flows to the City of Cape Town from WCWSS. In this regard, route 7 only represented the flows that were deemed to have been released to the City of Cape Town when the compensation flow releases and spillage of Kleinplaas Dam to Eerste River were met based on the simulated flows at the G2H005.

G2H020 Sub-Catchments

The G2H020 sub-catchments were G2H020-G22F, G2H020-G22G and G2H020-G22H. Figure 20 presents the configuration of these sub-catchments with the purple, pink and green colour networks representing the water flow in G2H020-G22F, G2H020-G22G and G2H020-G22H sub-catchments, respectively.

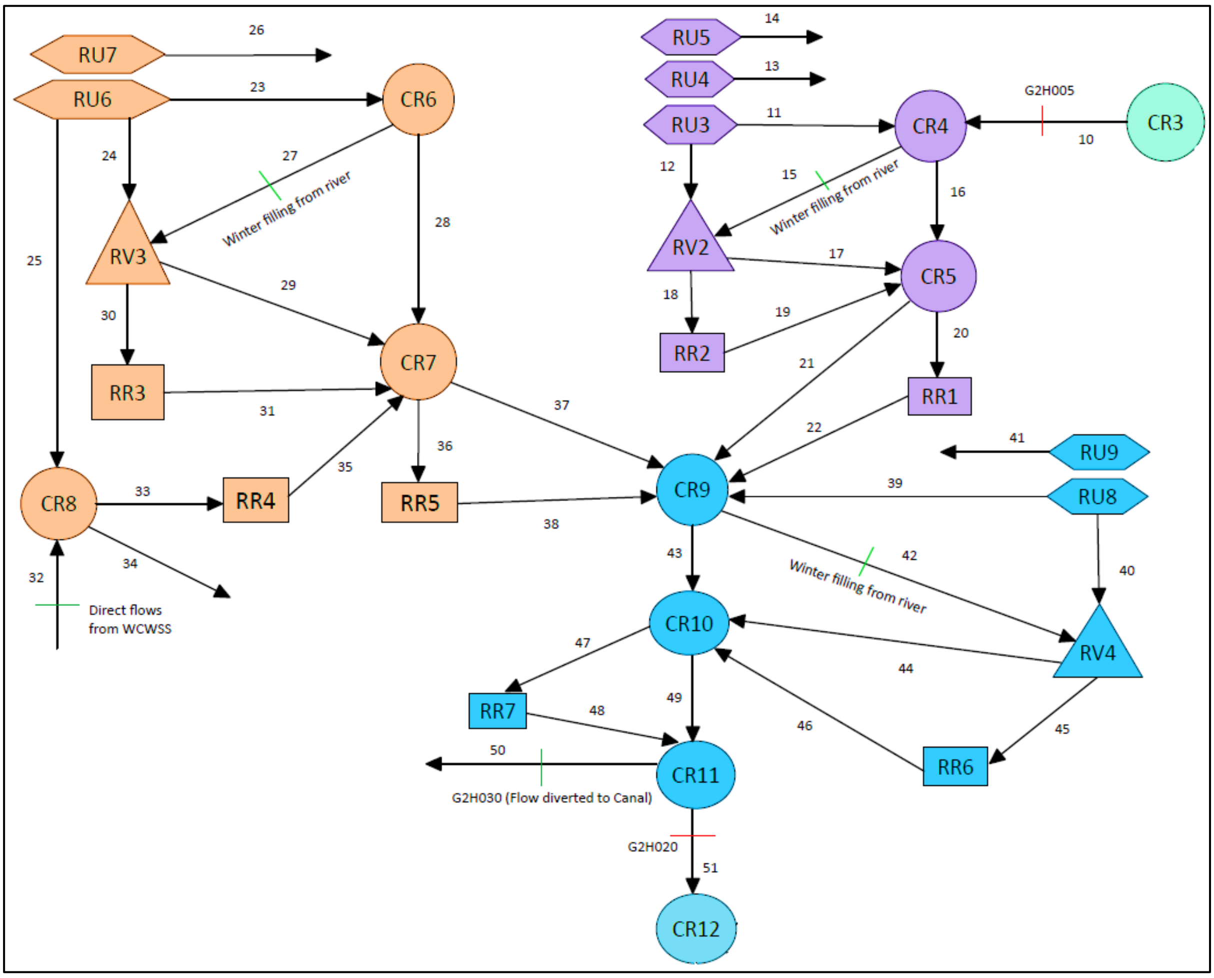

Figure 20: Configuration of G2H020 Sub-Catchments in Pitman Model

Figure 20 presents that G2H020-G22F sub-catchment was configured to generate naturalised flows through RU3 runoff module. The naturalised flows were then denaturalised by afforestation, and alien vegetation runoff modules denoted as RU4 and RU5, respectively. The denaturalised flows were then filling the farm dams represented by RV2, irrigation areas, and supplementing the existing flows in the Eerste River from G2H005-G22F sub-catchment measured at the G2H005. The irrigation modules denoted as RR1 and RR2 were then configured to utilise the flows from Eerste River and farm dams, respectively.

The G2H020-G22G sub-catchment was then configured to be generating naturalised flows from RU6 runoff module. These naturalised flows were then denaturalised by afforestation runoff module denoted as RU7. These denaturalised flows were then used to fill farm dams represented by RV3, in irrigation areas, and contributed to the exiting flows in the Eerste River that was flowing from G2H020-G22F sub-catchment. The irrigation modules represented by RR3 and RR5 were allocated water from farm dams and tributaries of Eerste River, respectively. The irrigation area supplied with water from WCWSS, distributed through pipelines to Stellenbosch Irrigation Board apart from accessing water from the catchment, was configured in the irrigation module denoted as RR4.

The G2H020-G22H sub-catchment was configured to generate naturalised flows through RU8 runoff module which were denaturalised by afforestation runoff module denoted as RU9. Similarly, to the configuration of G2H020-G22G and G2H020-G22F sub-catchments, the denaturalised flows were then utilised to fill the farm dams denoted as RV4, irrigation areas, and also supplementing the Eerste River flows from the upper sub-catchments.

The irrigation modules denoted as RR6 and RR7 were allocated water from the farm dams and the river, respectively. The compensation water releases from Kleinplaas Dam to irrigation areas downstream of this sub-catchment diverted by the canal were configured through route 50. The water abstractions from Eerste River through this canal is measured at the G2H030. Winter filling of farm dams was also configured as indicated by routes 15, 27 and 42. The remaining accumulated flows in Eerste River were compared with the observed flows at G2H020 gauging station located on route 51.

G2H040-G22H Sub-Catchment

The G2H040-G22H sub-catchment was configured in the Pitman model as highlighted in Figure 21.

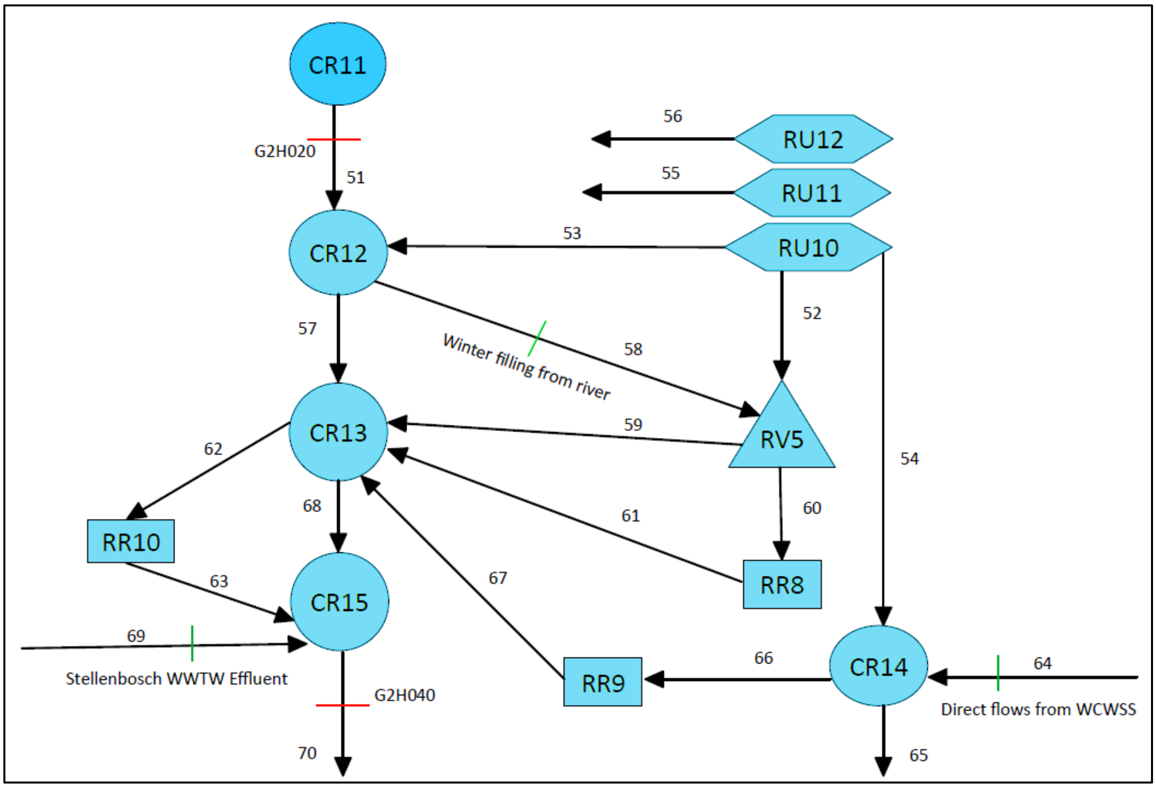

Figure 21: Configuration of G2H040-G22H Sub-Catchment in the Pitman Model

Figure 21 highlights that G2H040-G22H sub-catchment was configured in the Pitman model to generate naturalised flows from RU10 runoff module. These naturalised flows were then denaturalised by afforestation and alien vegetation runoff modules RU11 and RU12, respectively. The denaturalised flows were then allocated to farm dams represented as RV5, irrigation areas, and contributed to the Eerste River flows from G2H020 sub-catchments that had been measured at G2H020. The irrigation modules represented by RR8 and RR10 were then allocated water from farm dams and Eerste River, respectively. The irrigation areas accessing water from WCWSS through pipelines to Stellenbosch and Helderberg Irrigation Boards within the sub-catchment were configured in RR9 irrigation module.

The remaining simulated flows in the Eerste River were then supplemented by the treated effluent from the Stellenbosch Wastewater Treatment Works through route 69. The simulated flows were then compared to the observed flows at G2H040 to determine the plausibility of the calibration and validation of the model to represent the water resources in the Eerste River Catchment.

5.2.3 Calibration and Validation

The configured network of Eerste River Catchment in the Pitman model was calibrated and validated to determine the performance of the Pitman model in simulating the correct trend of the observed stream flows in the catchment. The calibration and validation modelling periods were 1983-2009 and 2009-2018, respectively. The criteria based on the recommendations by Bailey & Pitman (2016) and DWAF (2008a) for determining the goodness of fit of the simulated and observed streamflow, is presented in Table 12.

Table 12: Criteria for Goodness of Fit for Simulation in Pitman Model

Criteria	Recommended threshold
Mean Annual Runoff (MAR)	< 4%
Mean log Annual Runoff	< 4%
Standard deviation of annual flows	< 6%
Standard deviation of logs of annual flows	< 6%
Time series	As similar as possible
Seasonal Index	< 8%
Storage and Yield	As similar as possible

The criteria presented in Table 12 was achieved by adjusting the model calibration parameters that govern the surface and groundwater flow characteristics in the Pitman model. These model calibration parameters were based on the guidelines by Bailey & Pitman (2016) and are presented in Appendix C. The calibration parameters of the Eerste River Catchment provided in the WR2012 database, and those suggested by DWAF (2008a) were used as initial parameters in the calibration of the model. These parameters were then adjusted until the goodness of fit criteria was achieved, as presented in Table 12. The data that was used for the calibration is presented in Appendix D.

5.2.4 The Capacity of Farm Dams

The volume of farm dams was determined based on the area-capacity equation recommended by Bailey and Pitman (2016) expressed by Equation 11.

$$\text{Area} = A * \text{Capacity}^{B} \tag{11}$$

Where:

Area = farm dam area in km^2.

Capacity = farm dam capacity in Mm^3.

A and B = coefficients depending on the relationship of capacity and area of the farm dam

The coefficients A and B that were determined in DWAF (2008a) for farm dams in Eerste River Catchment were adopted in this research and are presented in Appendix D.

5.2.5 Land Use and Land Cover

The streamflow reduction by afforestation and alien vegetation was analysed using the Van der Zel and CSIR methods, respectively, described in Bailey & Pitman (2016). The Van der Zel method was chosen because the time-varying land use data that was available was not specific in terms of the plants that comprised the afforestation area. The only option was to analyse this data based on the time-varying of the afforestation areas, which in the Pitman model can only be done using Van der Zel method. The Van der Zel method in the Pitman model does not use the rotation period of afforestation. Therefore, the rotation period of afforestation was not considered in this research. As for Alien Vegetation, CSIR method was the only option in the Pitman model for analysing the alien vegetation; hence it was adopted.

5.2.6 Irrigation Demand

The irrigation water requirements were analysed based on the WQT model Type 2 method, explained in Bailey & Pitman (2016), in which monthly crop demand factors retrieved from WR2012 database, rainfall, A-Pan evaporation, and time-varying irrigation areas for the Eerste River Catchment were configured in the irrigation modules. The effective rainfall factor that was used in the irrigation modules was 0.75 and was based on the data retrieved from the WR2012 database for the Eerste River Catchment.

Based on the above information, the irrigation demand was then determined from the abstraction routes of the irrigation modules after the model run. Irrigation demands determined based on the modelling of the impact of climate change on Eerste River in the future periods were compared to the irrigation demand of the present-day period to quantify the influence of climate change impacted flows on irrigation demand in the catchment.

5.2.7 Modelling of Groundwater

The groundwater in the Eerste River Catchment was modelled using the SAMI groundwater module in the Pitman model. The properties of the groundwater aquifers in the G22F, G22G and G22H quaternary catchments were based on the data from WR2012 database. DWAF (2008a) reported that the SAMI groundwater module was not accurately accounting the groundwater in the catchments within the Berg Water Management Area in which Eerste River Catchment is located as highlighted in Chapter 2.

Bailey and Pitman (2016) reported that during the undertaking of the WR2012 study, the groundwater default parameters for every quaternary catchment in South Africa were revised, updated and used in the modelling of water resources in catchments within South Africa. It is in this vein that this research also adopted the use of the SAMI groundwater module.

5.2.8 Winter Filling of Farm Dams

This research also considered the winter filling of farm dams, as highlighted in Figure 18 and Section 3.1.6. The methodology that was used to model the winter filling of farm dams was adopted from DWAF (2008a). The steps that were followed were that the model was first calibrated and validated without considering winter filling of farm dams.

The simulated time series of the farm dams were then analysed to determine the amount of water that should be supplied from the nearby rivers to fill the dams during the winter period which was from May to September. The time series for the additional water from the nearby river was determined and configured to supply the farm dams in the model. The model was then calibrated and validated with consideration of winter filling of farm dams. Meeting the water requirements for winter filling of farm dams in the Pitman model depended on the available water from the river during the simulation. For example, if the water requirements were less than the available water in the river, then the water requirements were met, the opposite was also true.

5.2.9 Water Requirements from WCWSS

The water requirements from WCWSS for irrigation use in Lower Eerste River, Helderberg and Stellenbosch Irrigation Boards were also considered in the modelling of the Eerste River. The monthly time series for these water requirements were determined based on the procedure presented in Section 5.1.4. In this regard, these water requirements were configured in G2H020-G22F, G2H020-G22G and G2H040-G22H sub-catchments through route 9, route 32 and route 64, respectively as presented in Figure 18.

The G2H020-G22G and G2H040-G22H sub-catchments were selected because the farms in Stellenbosch and Helderberg Irrigation Boards, respectively, that were supplied with water from WCWSS through distribution pipelines were located in these two sub-catchments. The G2H020-G22F sub-catchment was considered because Kleinplaas Dam, through which the compensation water releases are conveyed to Eerste River, is located in this sub-catchment.

It must be restated that most of the compensation water releases are diverted from the Eerste River to the farms at G2H030 through the canal. The diverted flows from Eerste River to the canal were configured in the Pitman model through route 50, as presented in Figure 18.

5.2.10 Naturalised Flows and Available Water in the Eerste River Catchment

The naturalised flows generated from the quaternary catchments were determined after the model was calibrated and validated. This was undertaken by running the model with the ticked option of “simulate naturalised flows” in the runoff modules of the Pitman model. The naturalised flows were deemed to be the “available water” generated in the quaternary catchments. The reason was to determine if the available water generated in the catchments was enough to satisfy the changes in water demands that could arise due to the impact of climate change and developments scenarios.

Therefore, the available water in the G22G quaternary catchment was the water generated in G2H020-G22G sub-catchment and was compared to the changes in irrigation demand determined in this sub-catchment. Regarding the G22F quaternary catchment, this catchment comprised G2H005-G22F and G2H020-G22F sub-catchments which were separated by the Kleinplaas Dam as highlighted in Figure 17. The available water in G2H005-G22F sub-catchment was generated up to G2H005 with a catchment area of 31 km^2.

The area upstream of the Kleinplaas Dam encompassed 30 km^2 of this sub-catchment area, and the remaining 1 km^2 was for the area between the Kleinplaas Dam and G2H005. The proportion of the available water in the G2H005-G22F sub-catchment based on the area upstream of the Kleinplaas Dam was the available water upstream of the dam. This available water was compared with the changes in municipal water abstractions.

This approach was adopted because the intake weir for the Stellenbosch Municipality was located upstream of the Kleinplaas Dam. The remaining available water from the G2H005-G22F sub-catchment after meeting the municipal water abstractions was not considered to be flowing downstream of the Kleinplaas Dam because this water is diverted at the dam to meet the water demand of the City of Cape Town as highlighted in Section 2.3.1.

The changes in irrigation demand in G22F quaternary catchment were then compared to the available water downstream of the Kleinplaas Dam within the quaternary catchment because this is where the farms are located in this quaternary catchment as presented in Chapter 3. The available water in the G2H020-G22F sub-catchment and contribution from the available water from G2H005-G22F sub-catchment based on the proportion of the incremental area of 1km^2 between the Kleinplaas Dam and G2H005 were taken to be the available water for comparison with changes in irrigation demand in the G22F quaternary catchment.

As for the G22H quaternary catchment, the available water for the quaternary catchment was the summation of the available water in G2H020-G22H and G2H040-G22H sub-catchments as presented in Figure 17. This available water was compared with the changes in irrigation demands within the quaternary catchment.

The relative change in available water in the future periods compared to the present-day period was determined using Equation 10. The calculation of the relative change of the available water is illustrated in Table 13. In Table 13 it has been assumed that the available water was 15 Mm^3/a and 12 Mm^3/a in G22F catchment, and 30 Mm^3/a and 40 Mm^3/a in G22H catchment for the present-day and future periods, respectively.

Table 13: Calculation of Relative Change of Available Water in Catchment

Catchment	Available Water (Mm^3/a)		Relative Change (%)
	Present-Day Period (1)	Future Period (2)	(3) = [(2) – (1) / (1)] * 100
G22F	15	12	- 20.0
G22H	30	40	+33.3

Table 13 presents that the available water in G22F and G22H quaternary catchments are expected to decrease and increase by 20% and 33.3%, respectively, in the future period compared to the present-day period for illustration purposes.

6. Results and Discussion

This chapter presents the results and discussion of the research. The chapter starts with the presentation of results, then the discussion of results followed by a summary.

6.1 Results

The results are presented in four sections which are present-day naturalised flows in Eerste River, the impact of climate change on Eerste River, the impact of development scenarios on Eerste River, and the combined impact of climate change and development scenarios on Eerste River.

6.1.1 Present-Day Naturalised Flows in Eerste River

The present-day naturalised flows in Eerste River were determined for the 1983-2018 period, based on the methodology highlighted in yellow in Figure 22.

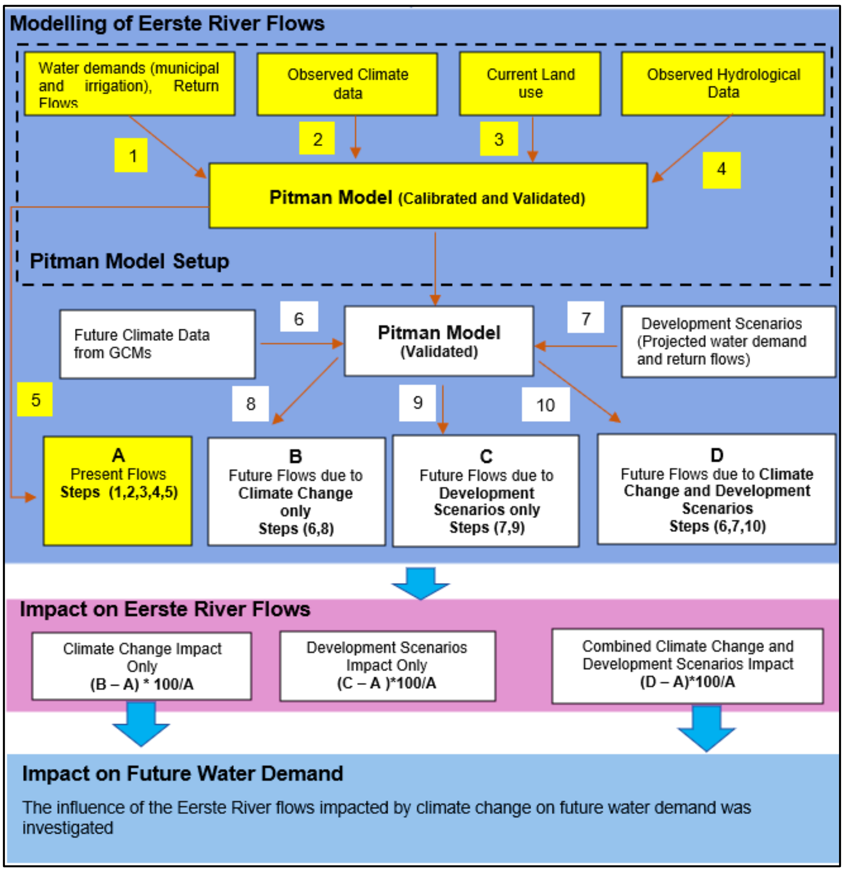

Figure 22: Methodology for the determination of the Present Flows

The Pitman model was calibrated and validated for 1983-2009 and 2009-2018 periods, respectively, to determine the accuracy of the model in representing the current status of the naturalised flows in the Eerste River. The results of the calibration and validation of the model and the determined present-day naturalised flows are presented in the following sections.

Calibration and Validation of the Eerste River in Pitman Model

The results of the calibration and validation of the Eerste River using the Pitman model are presented starting with G2H037 and G2H005 followed by G2H020 and G2H040.

G2H037 and G2H005 Gauging Stations

G2H037 and G2H005 are located in the G2H005-G22F sub-catchment. This sub-catchment is in the upper section of the Eerste River in the Jonkershoek Mountains, as presented in Figure 23.

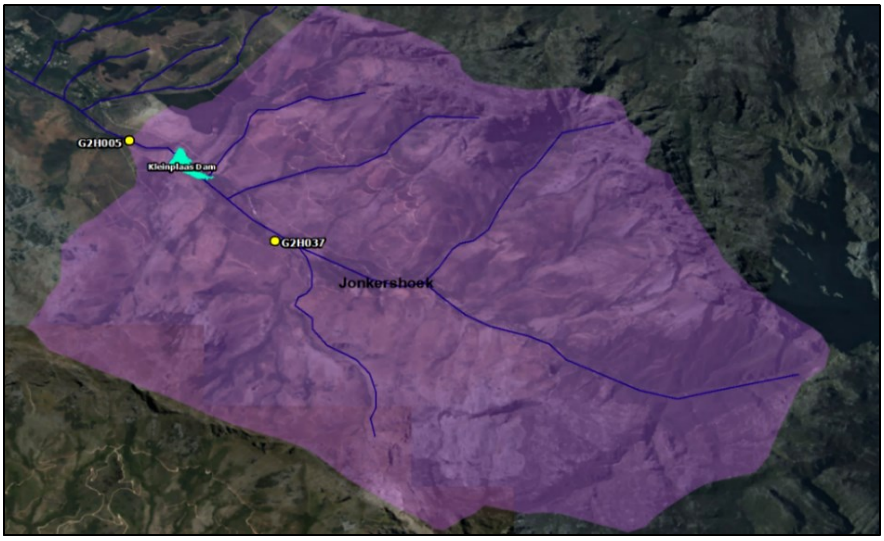

Figure 23: G2H005-G22F Sub-Catchment

The results of the Eerste River flows modelled at G2H037 and G2H005 are presented in Table 14.

Table 14: Eerste River flows at G2H037 and G2H005 Gauging Stations

G2H037				
Criteria	**Observed**	**Simulated**	**Difference (%)**	**Recommended Difference (%)**
Mean Annual runoff (Mm^3)	22.53	22.53	0.0	4
Mean log Annual Runoff	1.33	1.33	0.0	4
Standard deviation	7.44	7.08	-4.8	6
Standard deviation (log)	0.15	0.15	0.0	6
Seasonal Index	38.95	38.76	-0.5	8
G2H005				
Criteria	**Observed**	**Simulated**	**Difference (%)**	**Recommended Difference (%)**
Mean Annual runoff (Mm^3)	17.24	17.07	-1.0	4
Mean log Annual Runoff	1.19	1.20	+0.8	4
Standard deviation	7.47	6.34	-15.1	6
Standard deviation (log)	0.20	0.18	-10.0	6
Seasonal Index	32.28	33.86	+4.9	8

The results based on the graphical representation of the mean monthly hydrograph, monthly hydrograph and annual hydrograph at G2H037 and G2H005 are presented in Figure 24.

G2H037 Gauging Station **G2H005 Gauging Station**

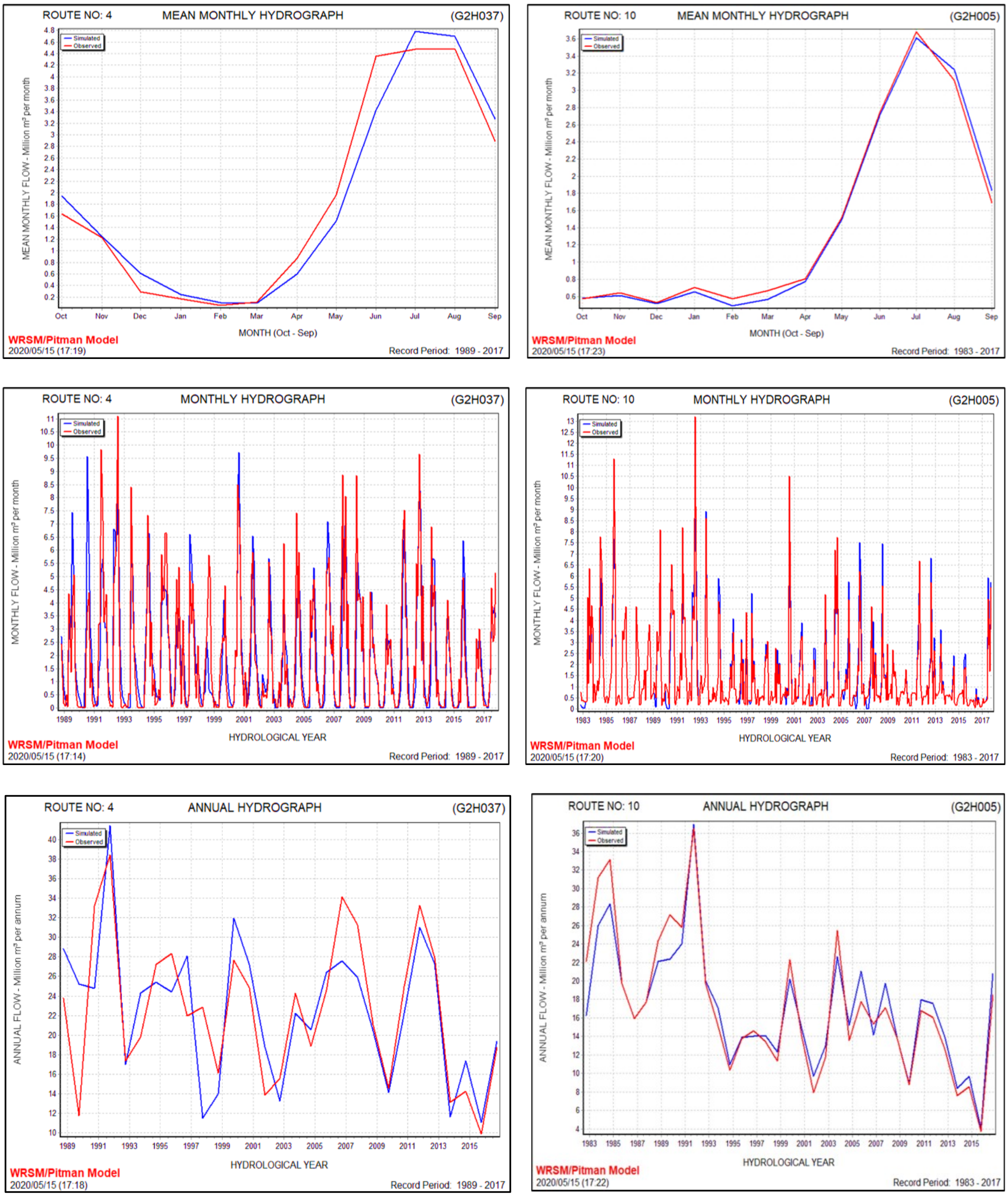

Figure 24: Hydrographs at G2H037 and G2H005 Gauging Stations

G2H020 Gauging Station

G2H020 is located in the middle section of the Eerste River Catchment which comprised G2H020-G22F, G2H020-G22G and G2H020-G22H sub-catchments. These sub-catchments are presented in Figure 25.

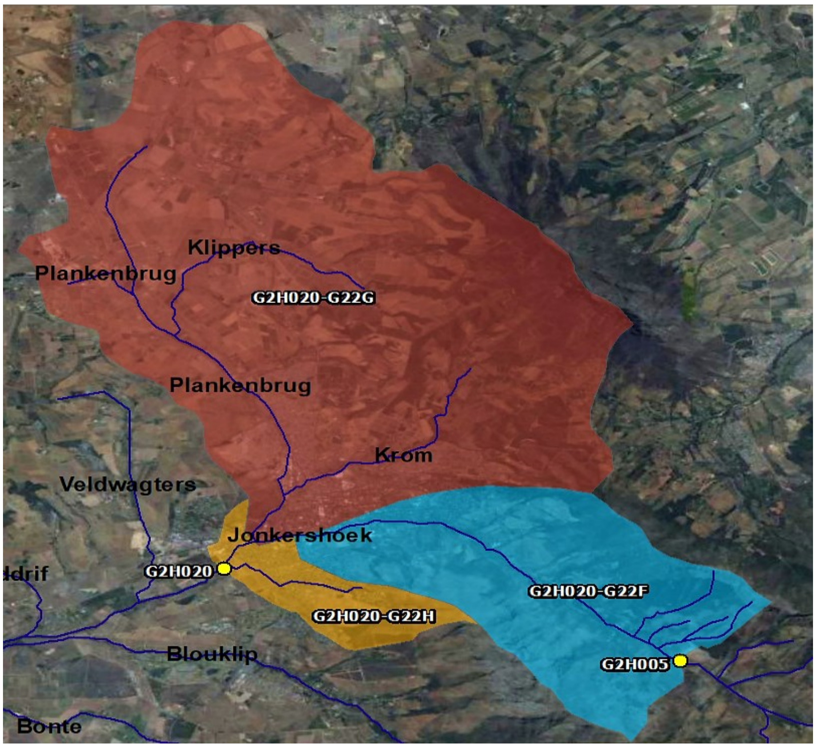

Figure 25: Sub-catchments for G2H020 Gauging Station

The results on the simulated and the observed flows at G2H020 are presented in Table 15.

Table 15: Simulated and Observed Flows at G2H020 Gauging Station

Criteria	Observed	Simulated	Difference (%)	Recommended Difference (%)
Mean Annual runoff (Mm^3)	38.56	38.56	0.0	4
Mean log Annual Runoff	1.54	1.54	0.0	4
Standard deviation	16.71	16.23	-2.9	6
Standard deviation (log)	0.21	0.21	0.0	6
Seasonal Index	40.66	40.70	+0.1	8

The results on the graphical representation of the monthly hydrograph, mean monthly hydrograph and annual hydrograph at G2H020 are presented in Figure 26.

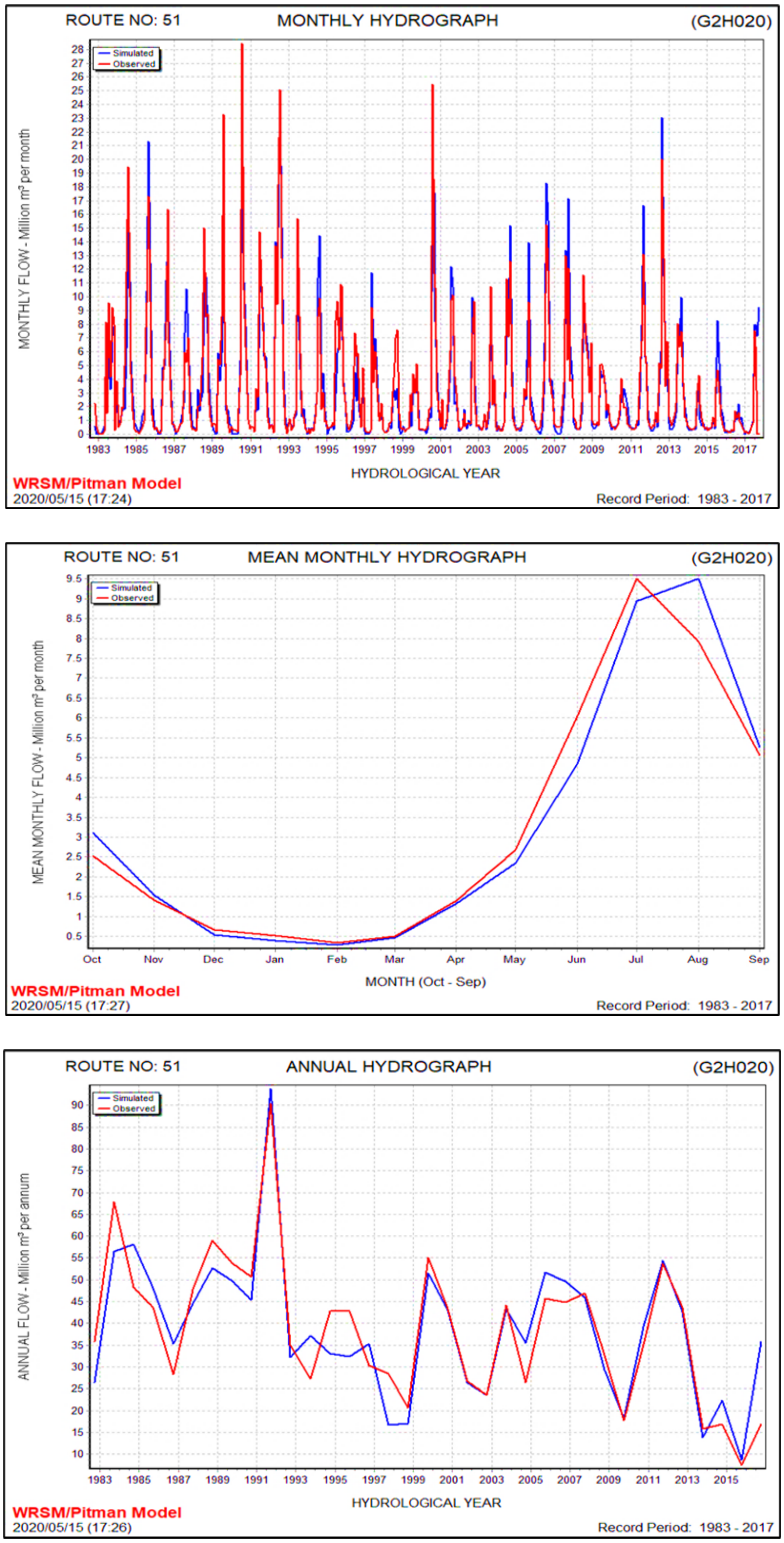

Figure 26: Hydrographs at G2H020 Gauging Station

G2H040 Gauging Station

G2H040 is located in the lower section of the Eerste River Catchment in G2H040-G22H sub-catchment as presented in Figure 27.

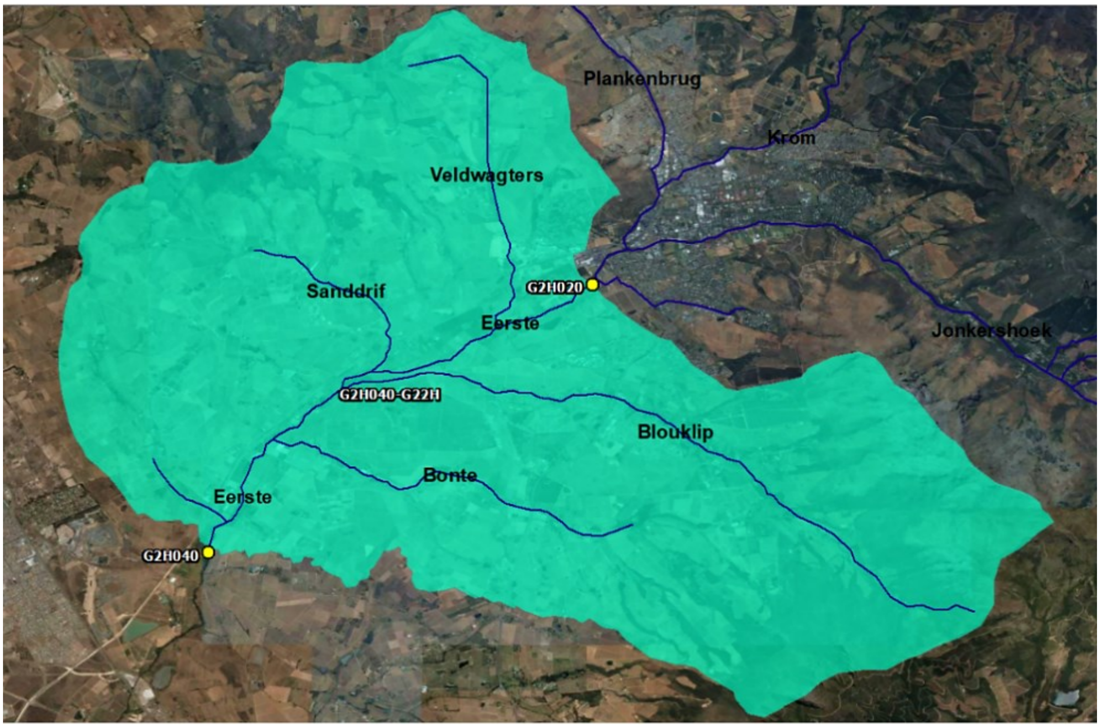

Figure 27: G2H040-G22H Sub-Catchment

The results of the calibration and validation of the model at G2H040 are presented in Table 16.

Table 16: Simulated and Observed Flows at the G2H040 Gauging Station

Criteria	Observed	Simulated	Difference (%)	Recommended Difference (%)
Mean Annual runoff (Mm^3)	56.59	56.59	0.0	4
Mean log Annual Runoff	1.72	1.72	0.0	4
Standard deviation	20.60	21.57	+4.7	6
Standard deviation (log)	0.18	0.19	+5.6	6
Seasonal Index	38.17	39.61	+3.8	8

The graphical representation of the mean monthly hydrograph, monthly hydrograph and annual hydrograph at G2H040 are presented in Figure 28.

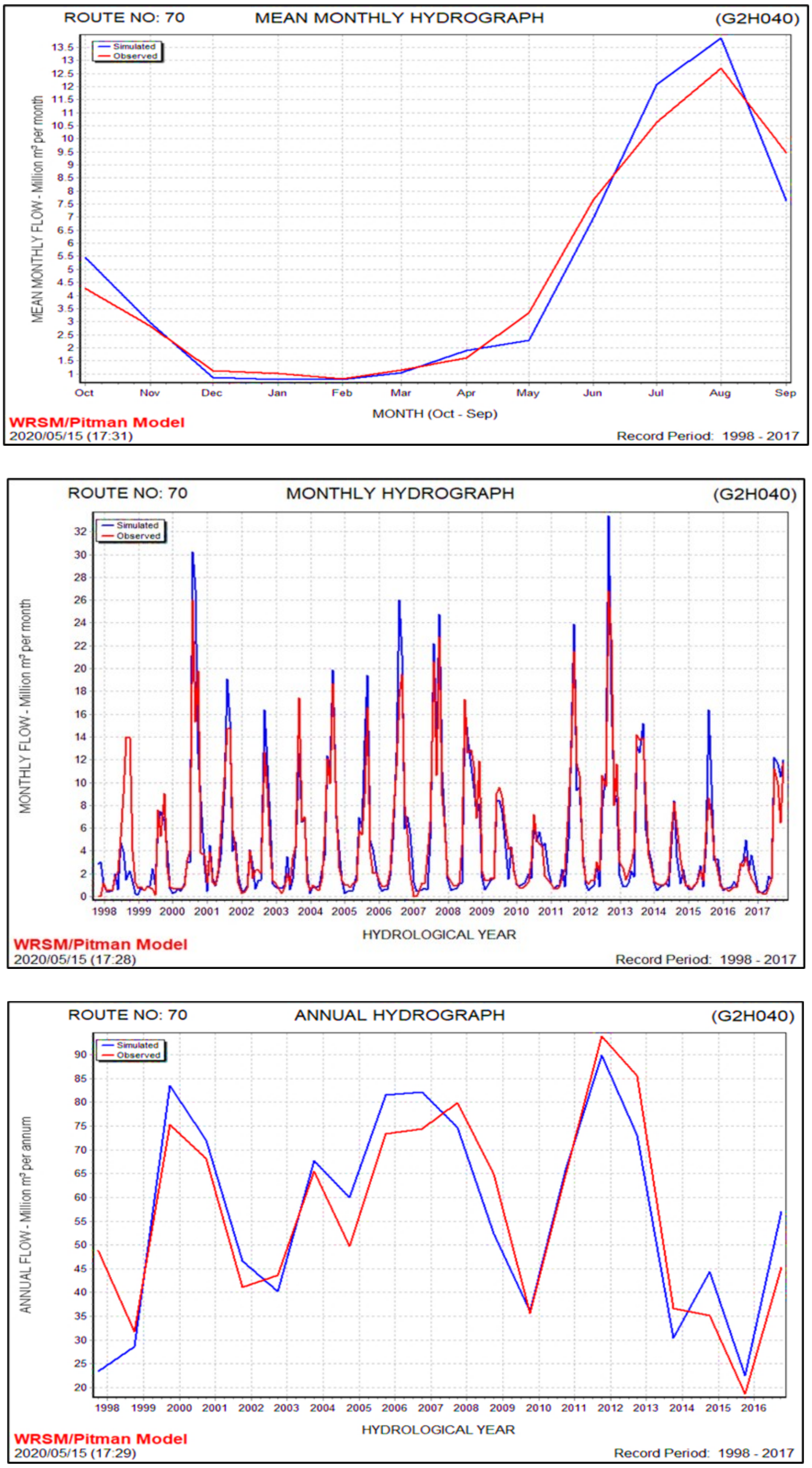

Figure 28: Hydrographs at G2H040 Gauging Station

Present-day naturalised flows were then determined based on the results from the calibrated and validated Pitman model. The results on the assessment of the present-day naturalised flows are presented in the next section.

Naturalised flows in Eerste River Catchment

The present-day naturalised flows were determined for the G22F, G22G and G22H quaternary catchments by ignoring the water demands, return flows (treated wastewater from Stellenbosch WWTW), water transfer from WCWSS and abstractions in the Pitman model. The naturalised flows for G22F quaternary catchment were the summation of naturalised flows for G2H005-G22F and G2H020-G22F sub-catchments. As for G22G quaternary catchment, the naturalised flows were those determined for the G2H020-G22G sub-catchment while for G22H quaternary catchment were the sum of naturalised flows for G2H020-G22H and G2H040-G22H sub-catchments. The results of the mean annual runoff of the naturalised flows in the Eerste River are presented in Table 17.

Table 17: Present-day Naturalised Flows in Eerste River

Catchment	Naturalised Flows (Mm^3)
G22F	39.68
G22G	16.38
G22H	55.42
Eerste River	111.48

The naturalised flows for the G22H quaternary catchment presented in Table 17 were determined for the area up to G2H040. Therefore, the naturalised flows for G22H quaternary catchment in this research did not represent the total naturalised flows for the whole G22H quaternary catchment area, as highlighted in Figure 13. The seasonal variation of the naturalised flows in the Eerste River Catchment is presented in Figure 29.

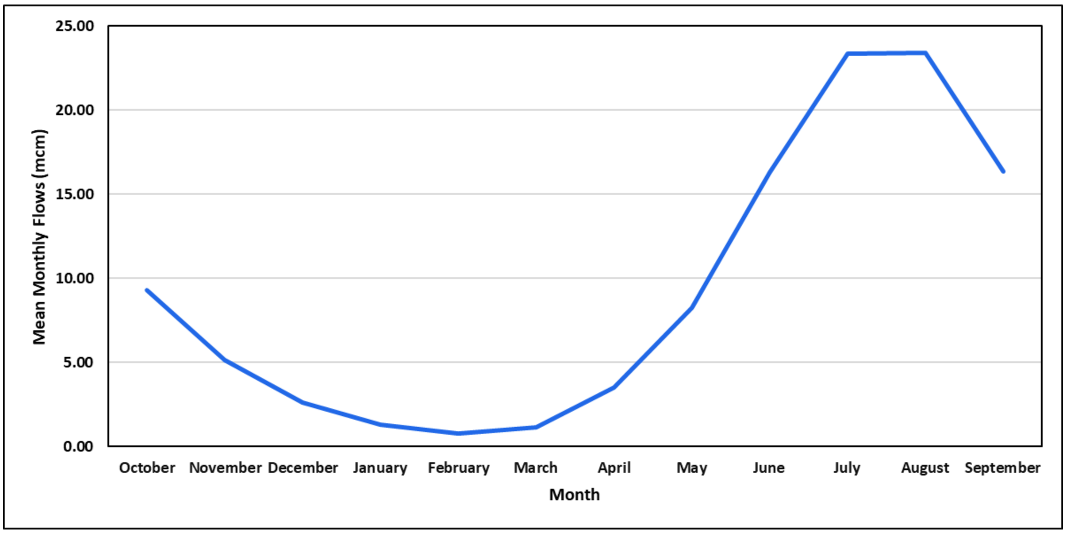

Figure 29: Seasonal Variation of Naturalised Flows in Eerste River

These naturalised flows determined in the quaternary catchments were accepted as the available water in the catchments. The results showed that the mean monthly flows of the available water in the Eerste River, especially in G22F quaternary catchment, where the intake weir of Stellenbosch Municipality is located, were adequate to meet the present-day abstraction pattern of the municipal water for the municipality, as presented in Figure 30.

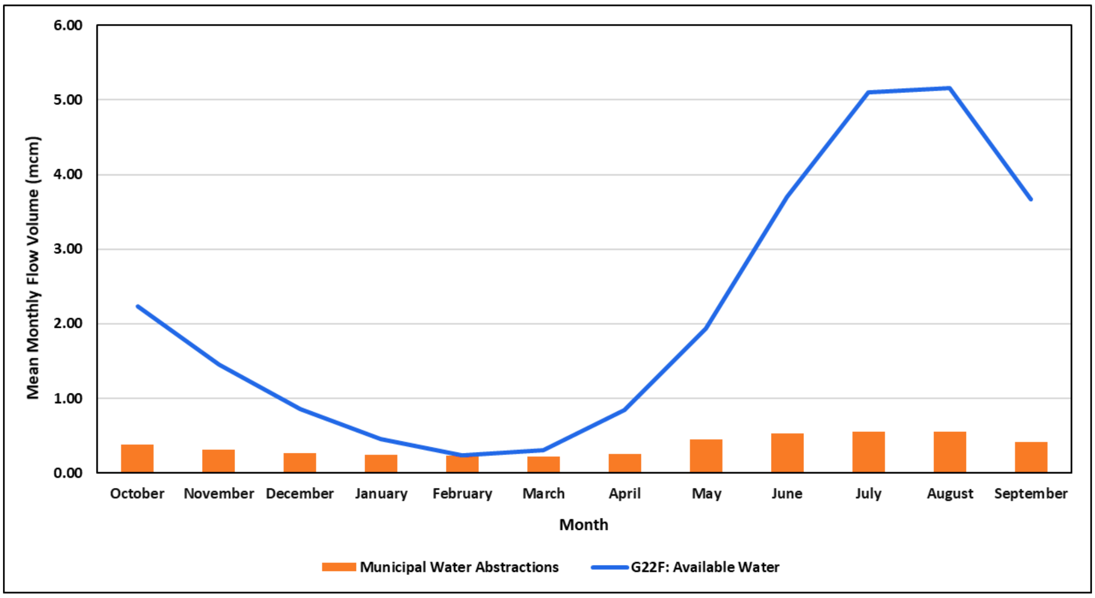

Figure 30: Available Water and Municipal Water Abstractions in G22F Catchment

The results also showed that the average municipal water abstraction from Eerste River by Stellenbosch Municipality, as determined in Pitman model, was 4.4 Mm^3/a for the 1983-2018 period, which was less than the capped water allocation of 7.224 Mm^3/a by DWS.

It can be observed that the available water in the Eerste River is not adequate to meet the seasonal variation of the irrigation demand, especially in the summer season in all quaternary catchments as presented in Figure 31. The deficit of the available water to meet the irrigation demand was estimated to be 44 Mm^3/a in Pitman model.

The results of the analysis of SANLC 2018 in ArcGIS indicated that more farms are in G22G and G22H catchments where the deficit of available water was more pronounced than in the G22F catchment.

Figure 31: Available Water and Irrigation Demand in Present-Day Period

After determining the present-day naturalised flows, the impact of climate change on the Eerste River was determined. The results on the impact of climate change on the Eerste River are presented in the next section.

6.1.2 Impact of Climate Change on Eerste River

The impact of climate change on the Eerste River was determined for the 2022-2057 (near) and 2058-2093 (far) future periods relative to the baseline or present-day period (1983-2018). The results will be presented by first highlighting the future climate of Eerste River Catchment under climate change, and then the impact of the climate change on the Eerste River.

6.1.2.1 Future Climate of Eerste River Catchment under Climate Change

This research utilised climate data generated by the 11 GCMs of CMIP5 forced by RCP 4.5 and RCP 8.5 to determine the climate change signal. The results on the analysis of the future evaporation and precipitation data are presented in the following sections.

Evaporation

The results of the GCM projection for climate change signal for evaporation are presented in Table 18. The table highlights that all GCMs projected an increase in evaporation in the future periods (climate change signal for all GCMs ≥ 1).

Table 18: GCM Projection of Climate Change Signal for Evaporation

GCM	RCP 4.5		RCP 8.5	
	2022-2057	2058-2093	2022-2057	2058-2093
MIROC-ESM	1.07	1.11	1.06	1.17
CNRM-CM5	1.05	1.10	1.06	1.14
CanESM2	1.07	1.09	1.07	1.15
FGOALS-s2	1.09	1.13	1.11	1.25
BNU-ESM	1.06	1.10	1.09	1.19
MIROC5	1.05	1.08	1.05	1.13
GFDL-ESM2G	1.03	1.03	1.04	1.09
MIROC-ESM-CHEM	1.05	1.09	1.06	1.17
GFDL-ESM2M	1.04	1.06	1.05	1.11
MRI-CGCM3	1.04	1.06	1.05	1.11
bcc-csm1-1	1.06	1.08	1.06	1.13

The GCMs projections for climate change signal were further compared to the criteria for uncertainty in the climate change signal, presented in Table 11. It can be noted that there is very high confidence that the increasing trend of evaporation would occur in the future, given that all GCMs projected a climate change signal of more than 1. The climate change signal for the monthly ensemble mean of GCMs based on the projections presented in Table 18 were then determined, and the results are presented in Table 19.

Table 19: Climate Change Signal for Monthly Evaporation

Month	RCP 4.5		RCP 8.5	
	2022-2057	2058-2093	2022-2057	2058-2093
October	1.06	1.09	1.06	1.16
November	1.07	1.10	1.07	1.16
December	1.05	1.08	1.06	1.15
January	1.05	1.08	1.06	1.14
February	1.05	1.07	1.06	1.13
March	1.05	1.07	1.06	1.13
April	1.06	1.07	1.07	1.15
May	1.06	1.08	1.06	1.16
June	1.05	1.09	1.07	1.16
July	1.05	1.08	1.07	1.16
August	1.05	1.10	1.07	1.16
September	1.06	1.09	1.07	1.16

The climate change signal (Table 19) was then compared to climate change signal of each GCM to determine the seasonal variation of the ensemble mean of GCMs relative to that of individual GCM as presented in Figure 32.

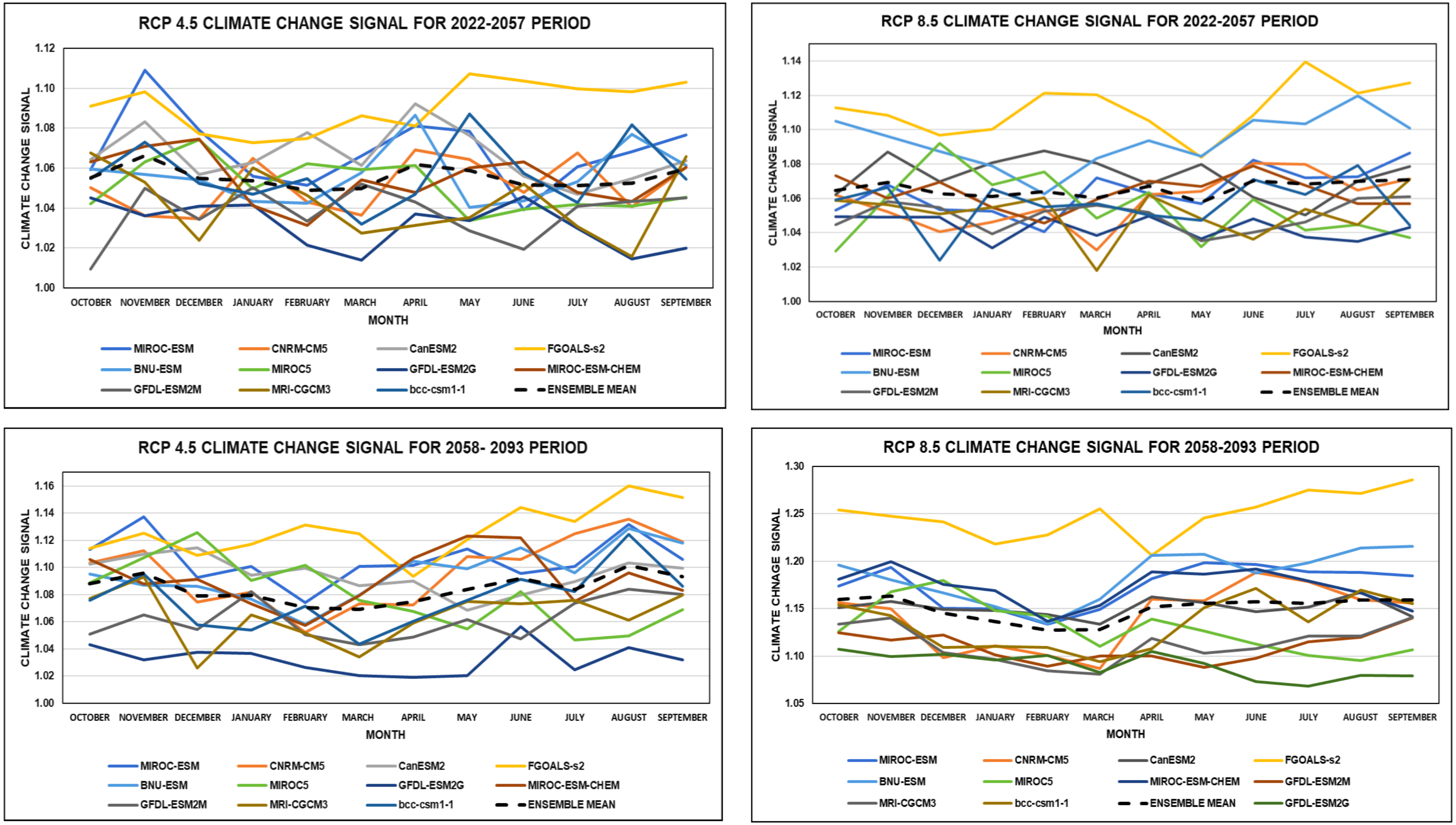

Figure 32: Seasonal Variation of the Climate Change Signal for Evaporation for RCP 4.5 and RCP 8.5

Figure 32 shows that climate change signal of the ensemble mean of GCMs and those of individual GCMs projected higher increase in evaporation in all the months of 2058-2093 period compared to the 2022-2057 period under both RCP 4.5 and RCP 8.5. It can be observed that the climate change signal is relatively lower in all the months under RCP 4.5 compared to RCP 8.5 in both future periods.

The climate change signal on evaporation highlighted in Figure 32 was relative to the future and present-day projection of the GCMs. Therefore, it did not represent the absolute change of the actual evaporation in the Eerste River Catchment. To determine the absolute change on evaporation in the catchment, the climate change signal of ensemble mean of GCMs was then transferred to the present day evaporation data in the Eerste River Catchment using Equation 6 as highlighted in Chapter 5. The relative change in evaporation between the future periods and present-day period was then determined using Equation 10.

The results indicated that there could be an average increase of evaporation of 6% and 7% in 2022-2057 period induced by RCP 4.5 and RCP 8.5, respectively, and also 8% and 15% in 2058-2093 period influenced by RCP 4.5 and RCP 8.5, respectively relative to the present-day period (1983-2018). The climate change-induced evaporation data determined for the Eerste River Catchment is presented in Appendix E.

The seasonal variation of evaporation in Eerste River Catchment is illustrated using the S-Pan Evaporation of G22F quaternary catchment for the future periods relative to the present-day period induced by RCP 4.5 and RCP 8.5 in Figure 33 and Figure 34, respectively.

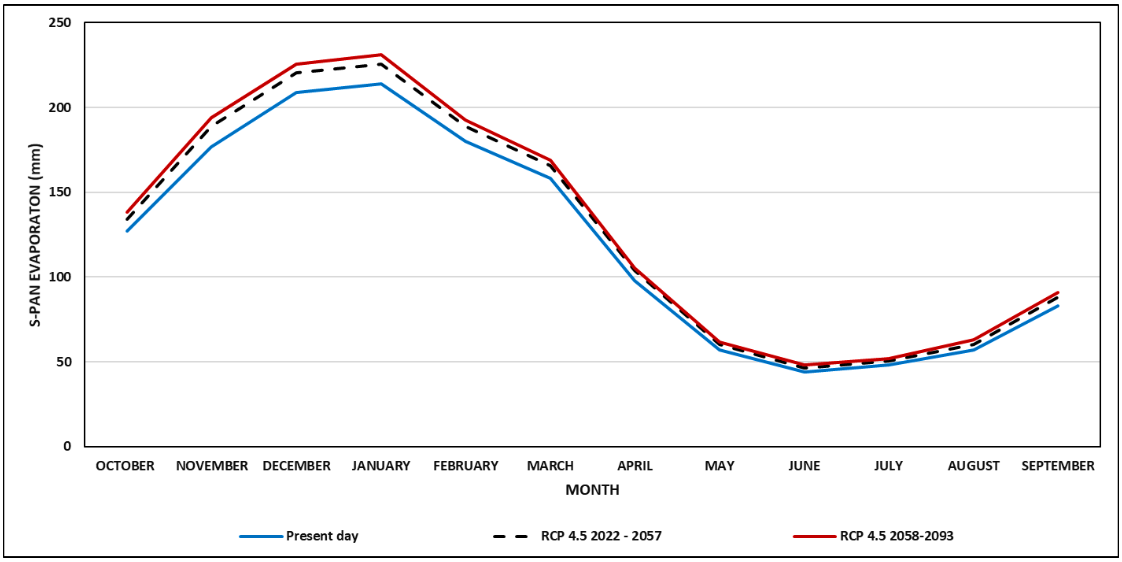

Figure 33: Seasonal Variation of S-PAN Evaporation induced by RCP 4.5 in G22F Catchment

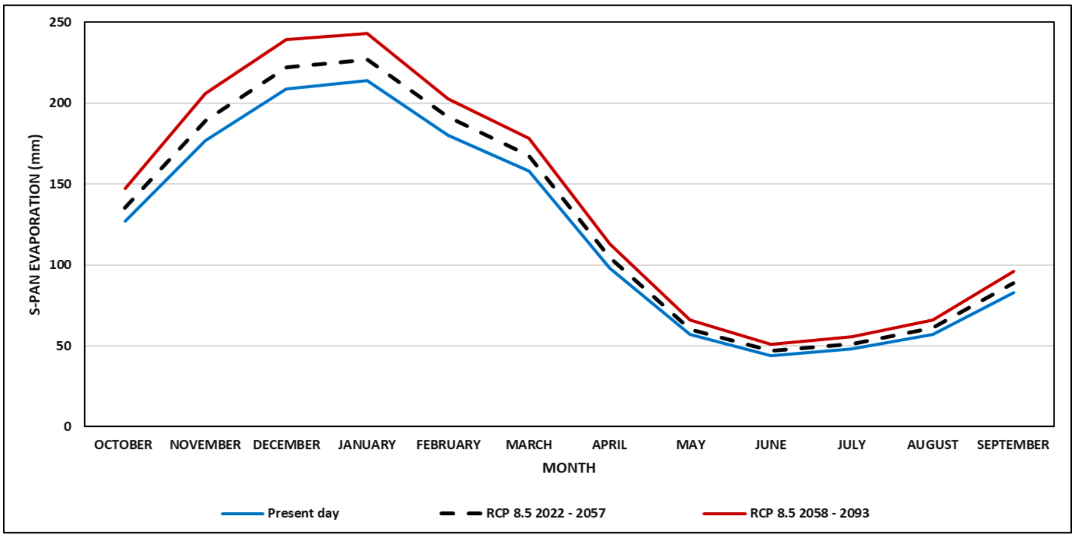

Figure 34: Seasonal Variation of S-PAN Evaporation induced by RCP 8.5 in G22F Catchment

Figure 33 and Figure 34 highlight that the evaporation pattern in the future periods is projected to remain the same relative to the present-day period but will only increase in magnitude. Evaporation is expected to be higher in the 2058-2093 period compared to the 2022-2057 period for both RCP 4.5 and RCP 8.5. The same trend was also discernible in the A-Pan evaporation of the Eerste River Catchment, but the results have not been presented in this section for the sake of brevity.

Precipitation

Similar, to evaporation, the climate change signal for precipitation for the 11 GCMs were determined for RCP 4.5 and RCP 8.5 in the 2022-2057 and 2058-2093 future periods relative to the present-day period. The results of the GCMs projection of the climate change signal for future precipitation are presented in Table 20.

Table 20: GCM Projection of Climate Change Signal for Precipitation

GCM	RCP 4.5		RCP 8.5	
	2022-2057	2058-2093	2022-2057	2058-2093
MIROC-ESM	0.94	0.90	1.05	0.95
CNRM-CM5	0.96	0.89	0.98	0.89
CanESM2	0.88	0.94	0.95	0.85
FGOALS-s2	0.95	1.01	0.90	0.82
BNU-ESM	0.98	0.94	0.94	0.84
MIROC5	0.95	0.91	1.00	0.89
GFDL-ESM2G	0.98	0.99	1.01	0.96
MIROC-ESM-CHEM	0.98	0.98	0.99	0.88
GFDL-ESM2M	0.98	0.97	1.04	0.94
MRI-CGCM3	1.01	1.00	1.02	0.99
bcc-csm1-1	0.95	0.94	0.98	0.86

Table 20 presents that the GCMs projected diverse direction of change of the climate change signal for future precipitation. It was noted under RCP 4.5 that 10 out of 11, and 9 out of 11 GCMs in 2022-2057 and 2058-2093 periods, respectively, indicated a decreasing trend in future precipitation. As for the RCP 8.5, it was observed that 6 out of 11, and all 11 GCMs in 2022-2057 and 2058-2093 periods, respectively, indicated a decreasing trend of the precipitation (projected climate change signal < 1)

There is, therefore, a medium to very high confidence that a decreasing trend in precipitation would occur in the future given that 6 of the 11 GCMs reflects a climate change signal of less than 1. The monthly climate change signal of ensemble mean of the 11 GCMs was then determined, and results are presented in Table 21.

Table 21: Climate Change Signal for Monthly Precipitation

Month	**RCP 4.5**		**RCP 8.5**	
	2022-2057	**2058-2093**	**2022-2057**	**2058-2093**
October	1.03	0.95	1.09	0.91
November	0.97	0.95	0.98	0.89
December	0.99	0.80	1.00	0.77
January	0.93	0.87	0.97	0.73
February	0.99	0.92	1.03	0.89
March	0.93	0.97	0.92	0.93
April	0.97	1.05	0.97	1.03
May	0.96	0.97	0.97	0.97
June	1.00	1.05	1.02	0.99
July	0.98	0.98	0.97	0.98
August	0.92	1.00	0.99	0.86
September	0.86	0.93	0.93	0.81

The climate change signal of the monthly ensemble mean of GCMs as presented in Table 21 was then compared with the climate change signal of each GCM to determine the seasonal variation of the climate change signal in the future under the RCP 4.5 and RCP 8.5 as presented in Figure 35.

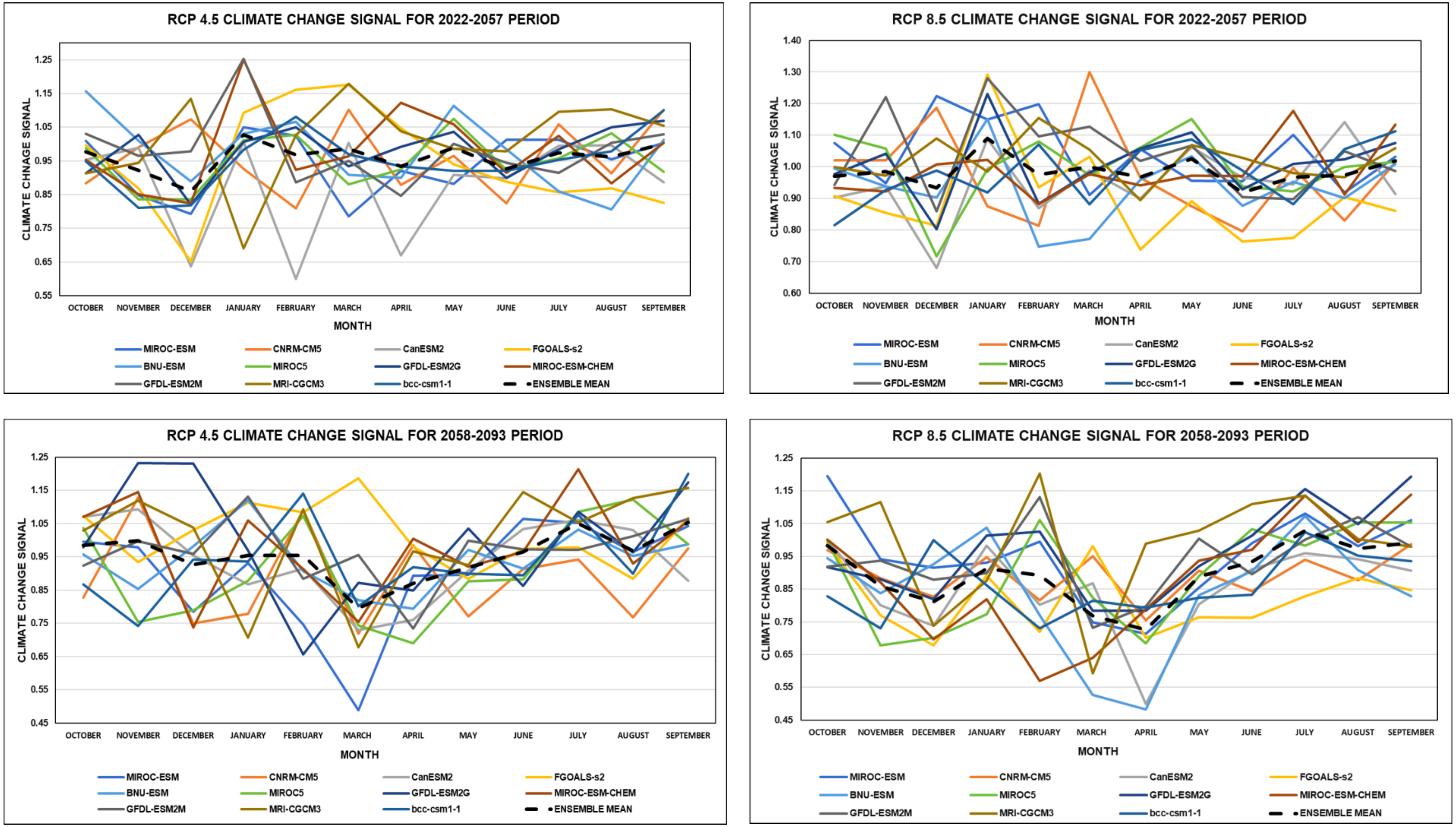

Figure 35: Seasonal Variation of the Climate Change Signal for Precipitation for RCP 4.5 and RCP 8.5

Figure 35 shows that a decreasing trend of precipitation due to climate change was projected for both RCP 4.5 and RCP 8.5 trajectories in the 2022-2057 and 2058-2093 periods. This decreasing trend is expected to be more significant in December compared to the other months in the hydrological year in the 2022-2057 period. As for the 2058-2093 period, it was projected that precipitation could decrease more in March and April in RCP 4.5 and RCP 8.5, respectively, compared to other months in the hydrological year.

The climate change signal on the precipitation highlighted in Figure 35 was relative to the future and present-day projection of the GCMs. Therefore, it did not represent the absolute change of the actual precipitation in the Eerste River Catchment. The climate change signal was then transferred to the present-day rainfall data of the Eerste River Catchment using Equation 6 to determine the absolute change of the precipitation in the catchment.

The present-day rainfall data for the Eerste River Catchment was the rainfall for zone G2C as presented in Chapter 5 and using Equation 10, the change in rainfall between future periods and present-day period was determined. The impact of climate change signal on the precipitation of the Eerste River Catchment indicated that there could be an average decrease of precipitation of 4% and 2% in 2022-2057 period for RCP 4.5 and RCP 8.5, respectively, and also 3% and 8% in 2058-2093 period for RCP 4.5 and RCP 8.5, respectively, relative to the present-day period (1983-2018).

The climate change-induced precipitation data of Eerste River Catchment in the future periods is presented in Appendix F. Figure 36 and Figure 37 present the seasonal variation of rainfall induced by RCP 4.5 and RCP 8.5, respectively, in future periods relative to present-day period. This seasonal variation of precipitation is based on precipitation data in Appendix F.

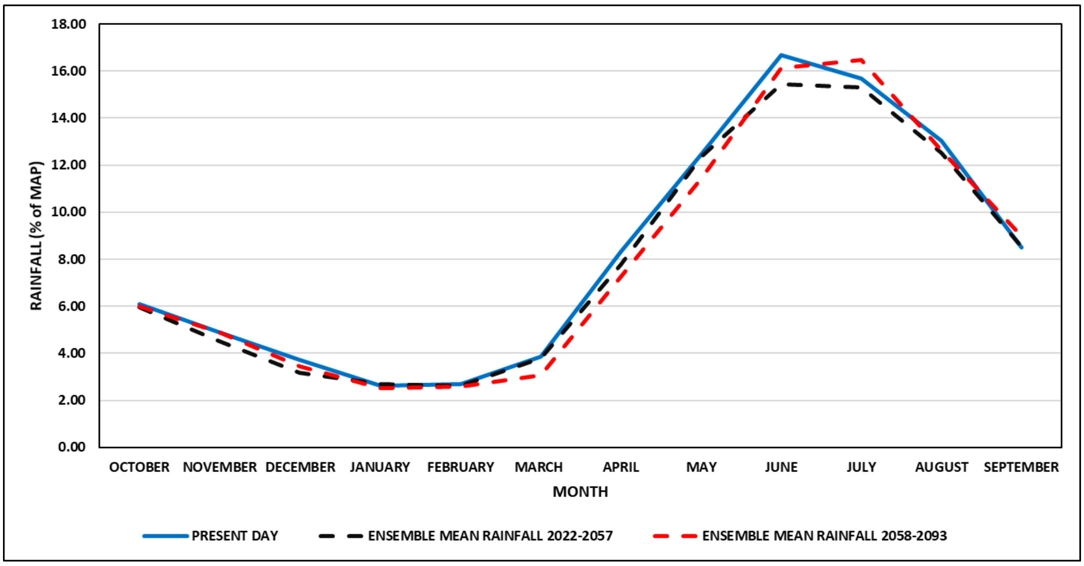

Figure 36: Seasonal Variation of Rainfall induced by RCP 4.5

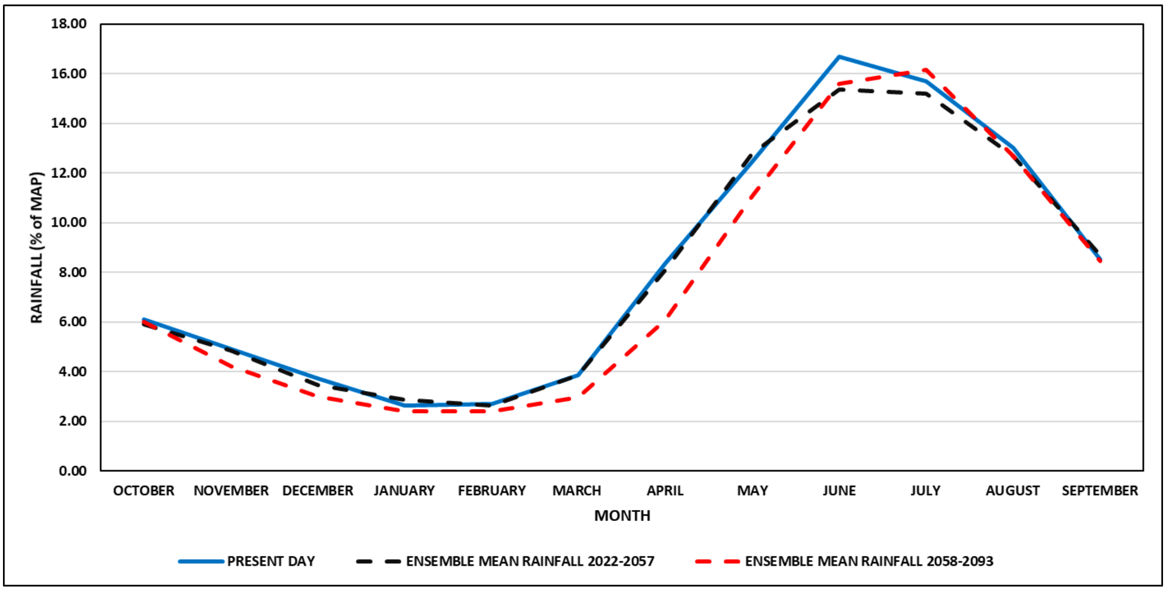

Figure 37: Seasonal Variation of Rainfall induced by RCP 8.5

Figure 36 and Figure 37 show that there will be a shift in the occurrence of peak mean monthly rainfall from June to July in far-future period relative to the present-day period under RCP 4.5 and RCP 8.5, respectively. Figure 36 presents that rainfall is expected to be lower from January to May in 2058-2093 period relative to 2022-2057 period, in the opposite way, rainfall will be lower from June to December in 2022-2057 period relative to 2058-2093 period based on the influence of RCP 4.5. Figure 37 indicates that if the future climate follows the RCP 8.5 trajectory, rainfall is expected to be lower between October to May in the 2058-2093 period relative to the 2022-2057 period while in June to September it would be vice versa.

The climate change-induced evaporation and precipitation data that were determined in this section were then used in the modelling of the Eerste River to determine the impact of climate change on the river flow. The results of the impact of climate change on the flow in the Eerste River are presented in the next section.

6.1.2.2 Impact of Climate Change on Eerste River

The impact of the climate change on the flow in the Eerste River was assessed using the climate change-induced evaporation, and rainfall data in the Pitman model. The changes in the flows of the Eerste River were determined based on the methodology highlighted in yellow in Figure 38.

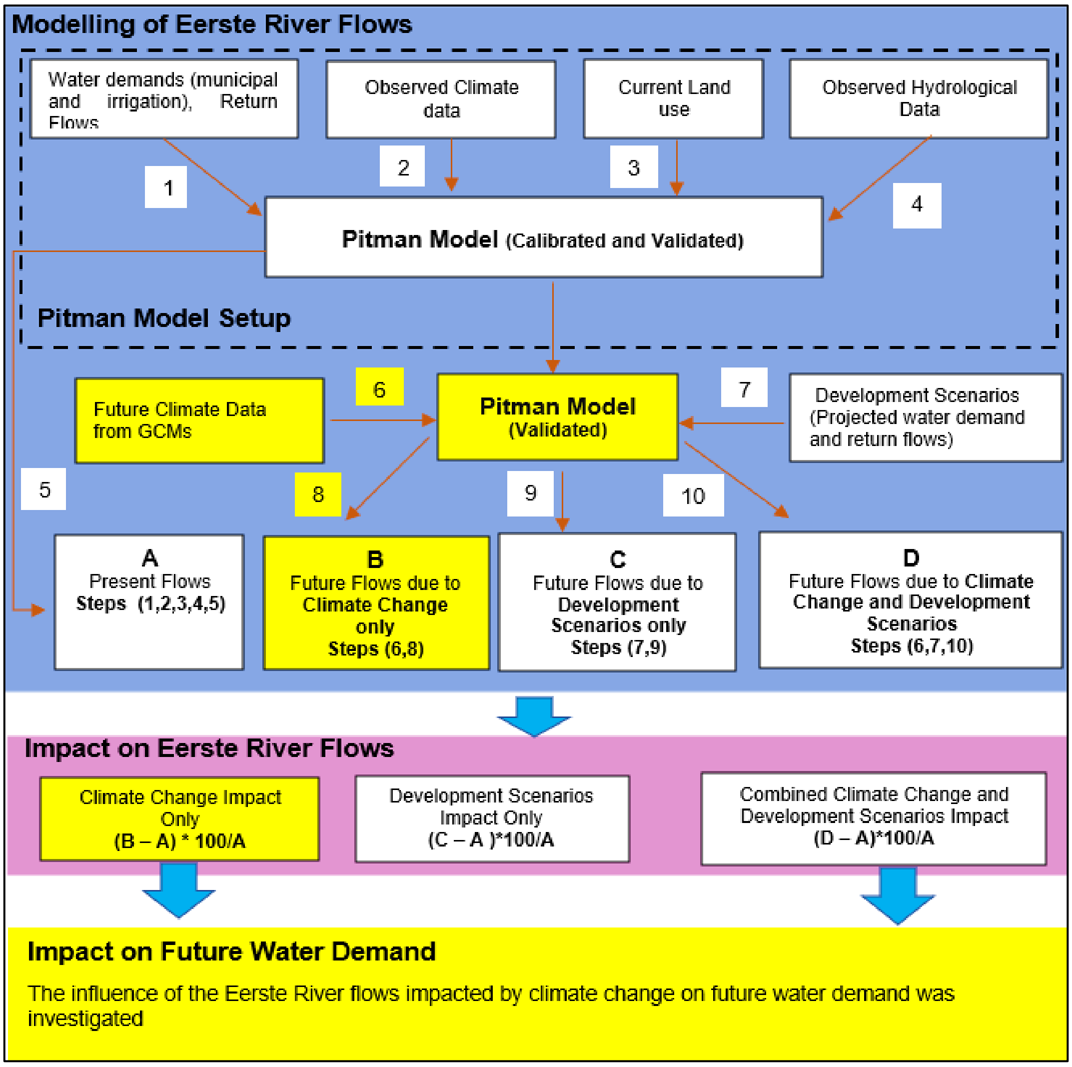

Figure 38: Methodology for Determining the Impact of Climate Change

The results of the impact of climate change on the mean annual runoff in the Eerste River at the G2H037, G2H005, G2H020 and G2H040 gauging stations in the future periods are presented in Table 22.

Table 22: Impact of Climate Change on River Flows at Gauging Stations

Gauging Station	2022-2057		2058-2093	
	Change %		Change %	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
G2H037	-9.0	-8.0	-8.0	-17.0
G2H005	-2.5	-2.0	-2.3	-5.0
G2H020	-11.9	-11.0	-12.1	-22.0
G2H040	-9.5	-9.0	-8.9	-19.0

Table 22 shows that there will be a decreasing trend on the mean annual runoff at the gauging stations in both 2022-2057 and 2058-2093 periods compared to the present-day period because of climate change. Based on results in Table 22, the flows at the outlet of the Eerste River Catchment, which were modelled at G2H040, are expected to be 51 Mm^3/a and 51.7 Mm^3/a under RCP 4.5 and RCP 8.5, respectively, in the 2022-2057 period. In the 2058-2093 period, the flows at G2H040 are anticipated to be 51.6 Mm^3/a and 46 Mm^3/a under RCP 4.5 and RCP 8.5, respectively. The results of the impact of climate change on available water (naturalised flows) within the catchments in the future periods relative to the present-day period are presented in Table 23.

Table 23: Impact of Climate Change on the Available Water in Eerste River Catchment

Catchment	**2022-2057**		**2058-2093**	
	Change (%)		**Change (%)**	
	RCP 4.5	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
G22F	-10.1	-9.0	-10.0	-20.0
G22G	-13.0	-12.0	-13.4	-25.0
G22H	-7.9	-7.0	-7.5	-15.0
Eerste River	-9.4	-8.0	-9.2	-18.0

Table 23 presents that there will be more reduction in available water due to climate change under RCP 8.5 than RCP 4.5 in the 2058-2093 period and in the opposite way in 2022-2057 period. It was noted that the available water is expected to reduce more in G22G quaternary catchment compared to the G22F and G22H quaternary catchments in both future periods. The seasonal pattern of mean monthly flows of the available water in the Eerste River Catchment under RCP 4.5 and RCP 8.5 were deemed to be the same in both future and present-day periods as presented in Figure 39 and Figure 40, respectively.

Figure 39 also highlights that under RCP 4.5, the mean monthly flows of the available water will be lower in winter season especially between July to September in the 2022-2057 period compared to the 2058-2093 period while in summer season it will be in the opposite way. Climate change under RCP 8.5 was noted to cause a decreasing trend in the mean monthly flows of available water across all the months in the hydrological year in both future periods relative to the present-day period as presented in Figure 40.

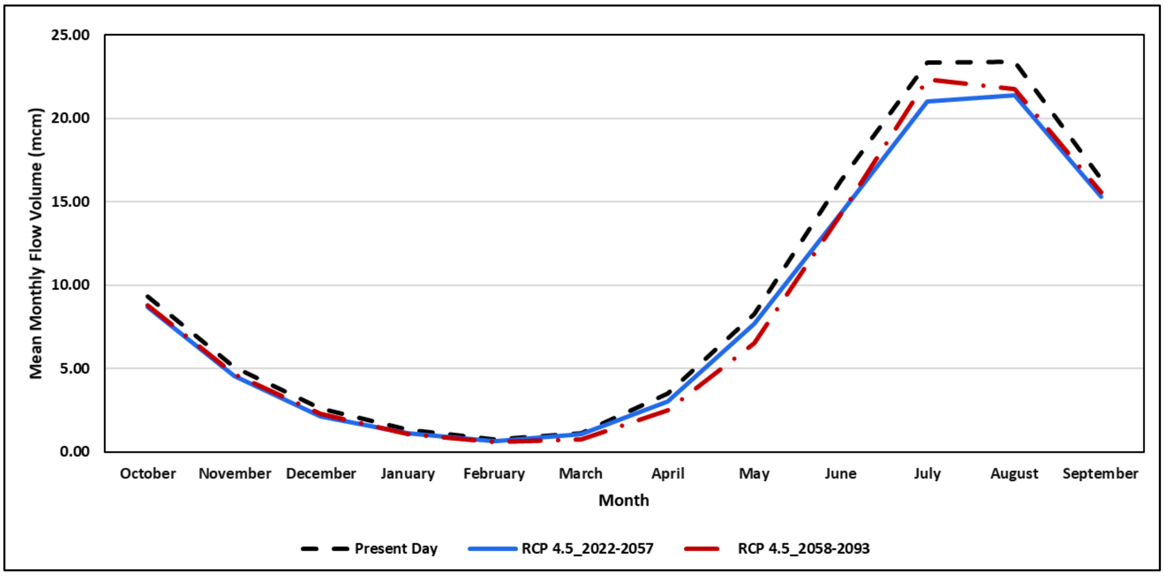

Figure 39: Seasonal Variation of Available Water in Eerste River Catchment under RCP 4.5

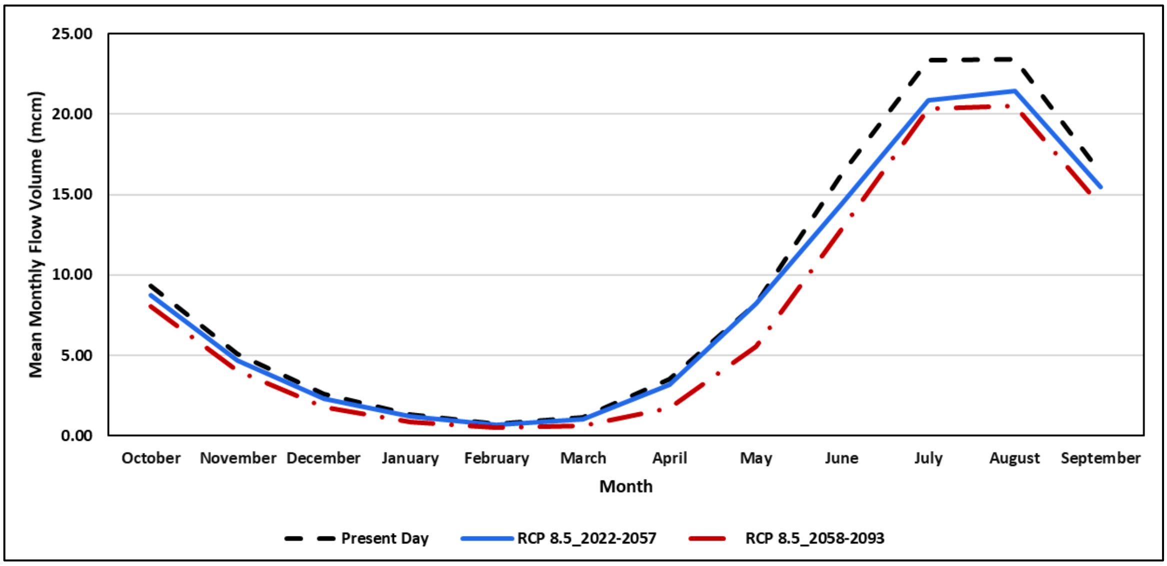

Figure 40: Seasonal Variation of Available Water in Eerste River Catchment under RCP 8.5

The results also showed that there could be no impact on the municipal water abstractions due to the reduction of available water in the future periods under the influence of RCP 4.5, as presented in Figure 41. In other words, neither increase nor decrease or failure to meet the present-day municipal abstractions is expected in the future periods. The same pattern was noted under the RCP 8.5 trajectory of climate change in the 2022-2057 period. Additionally, failure to meet the municipal water abstractions was noted in the 2058-2093 period which was more pronounced in February and March as presented in Figure 42.

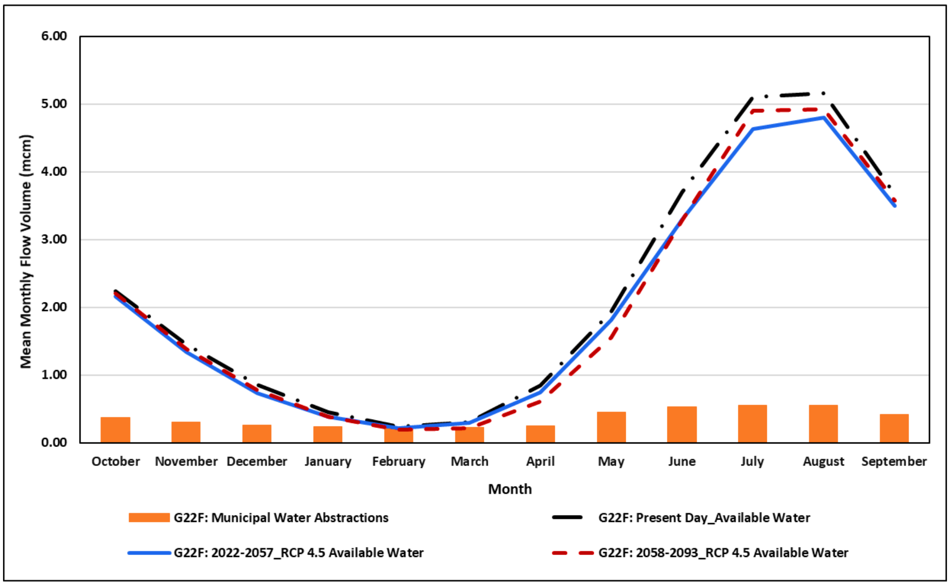

Figure 41: Available Water and Municipal Water Abstractions under RCP 4.5

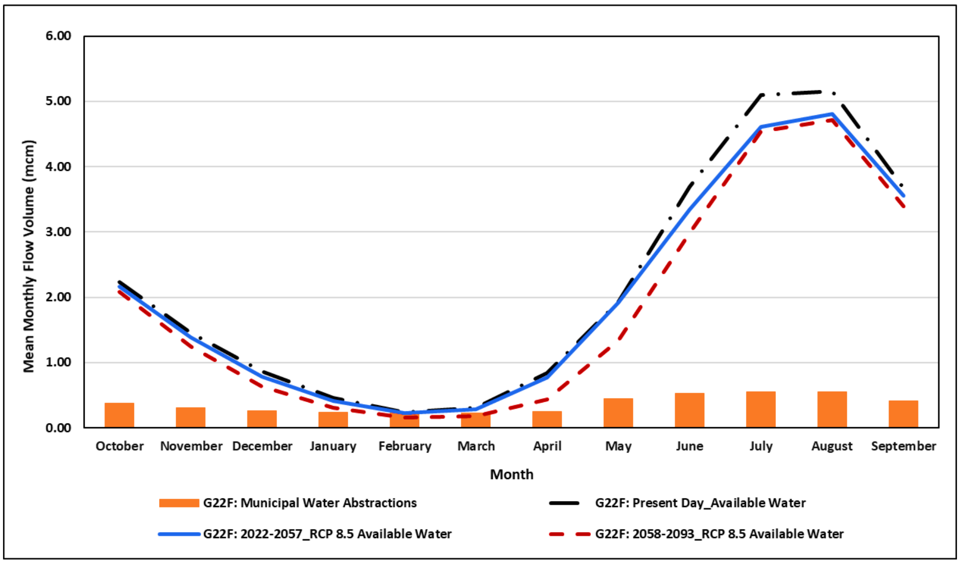

Figure 42: Available Water and Municipal Water Abstractions under RCP 8.5

It is expected that climate change would potentially trigger an increase in water requirement for irrigation use. This increase in irrigation demand was determined using Equation 10. The results showed that an increase in irrigation demand of 12.1% and 11.7% could be triggered under RCP 4.5 and RCP 8.5, respectively, in 2022-2057 period while in 2058-2093 period, it could be 17% and 29% under RCP 4.5 and RCP 8.5, respectively.

It was determined with the Pitman model that this increase in irrigation demand could be 5.3 Mm^3/a and 7 Mm^3/a in the 2022-2057 and 2058-2093 periods, respectively, under the impact of climate change influenced by RCP 4.5. Under the impact of climate change enforced by RCP 8.5, the demand was determined to be 5.1 Mm^3/a and 13 Mm^3/a in the near and far future periods, respectively.

The seasonal variation of available water and irrigation demand under both RCP 8.5 and RCP 4.5 was the same but different in the magnitude of change. For the sake of brevity, only seasonal variation under RCP 8.5 is presented, as shown in Figure 43.

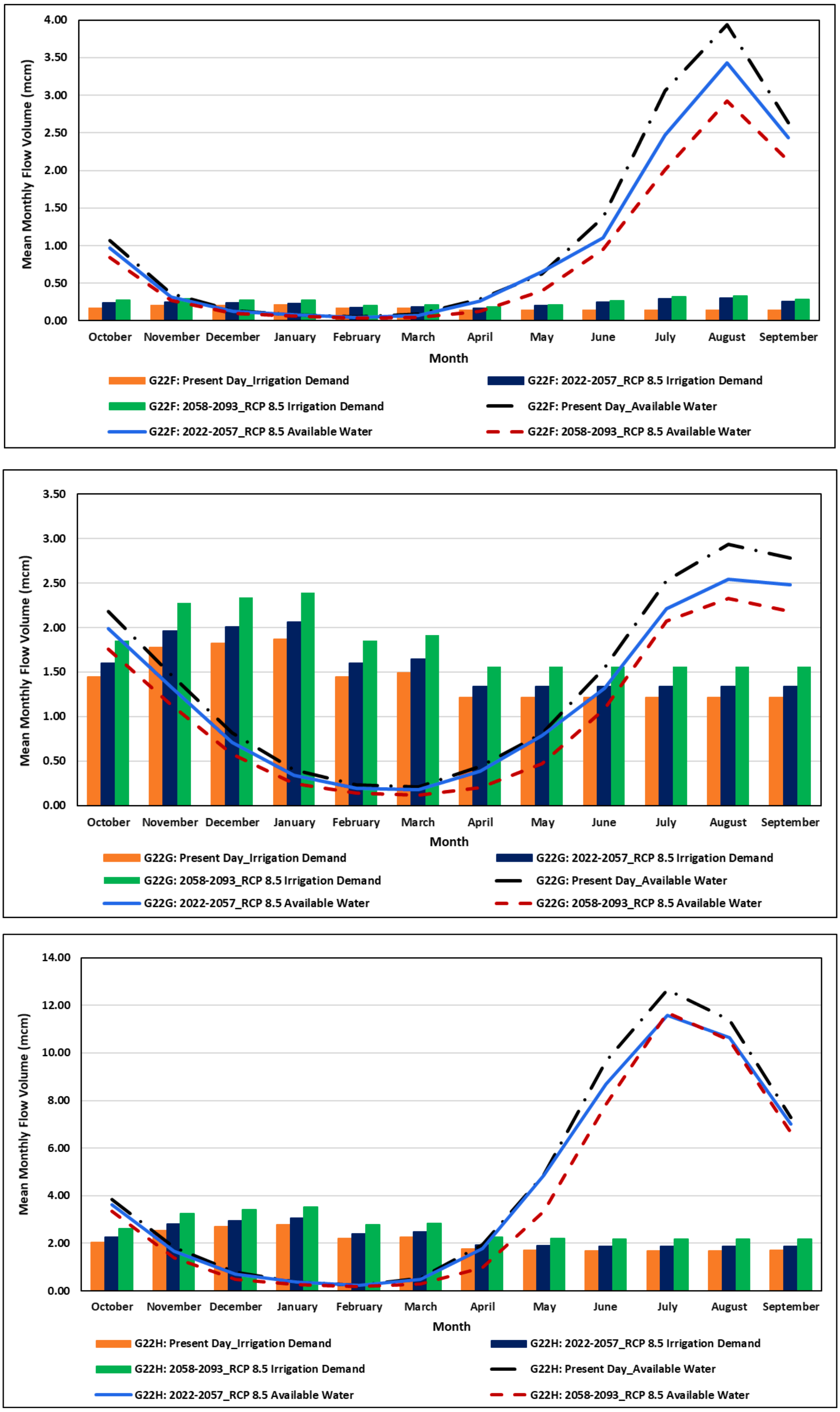

Figure 43: Available Water and Irrigation Demand under RCP 8.5

Figure 43 highlights that the reduction in available water would exacerbate meeting the irrigation demand, especially in the summer season in the future periods relative to the present-day period. The inadequacy of available water to meet the irrigation demand was more pronounced in the 2058-2093 period than in 2022-2057 period. The results also showed that the increase in irrigation demand could be higher in G22G and G22H quaternary catchments than in G22F quaternary catchment.

6.1.3 Impact of Development Scenarios on Eerste River

The impact of development scenarios on the Eerste River was determined based on the Low and High Development scenarios. In the Low and High Development Scenarios, municipal water requirements were expected to grow at 2% and 3% per annum, respectively, with no anticipated growth in irrigation water requirements based on the increased area of irrigated agriculture in both scenarios in the near-future period.

The results showed that the municipal water abstractions for the Stellenbosch Municipality from Eerste River based on the Low and High Development Scenarios are expected to increase from 4.68 Mm^3/a to 9.36 Mm^3/a and 13.17 Mm^3/a, respectively, at 2057. The municipal water abstractions of 4.68 Mm^3/a was adopted for the year 2022 based on the procedure presented in Chapter 5.

It was observed that the current capped water allocation for municipal water abstractions of 7.224 Mm^3/a from Eerste River for Stellenbosch Municipality could be exceeded in 2045 and 2037 in low and high development scenarios, respectively, as presented in Figure 44. This increase in municipal water abstractions in low and high development scenarios represented a 30% and 82% increase, respectively, relative to the present-day water allocation of 7.224 Mm^3/a. The projected municipal water abstractions under development scenarios are in Appendix G.

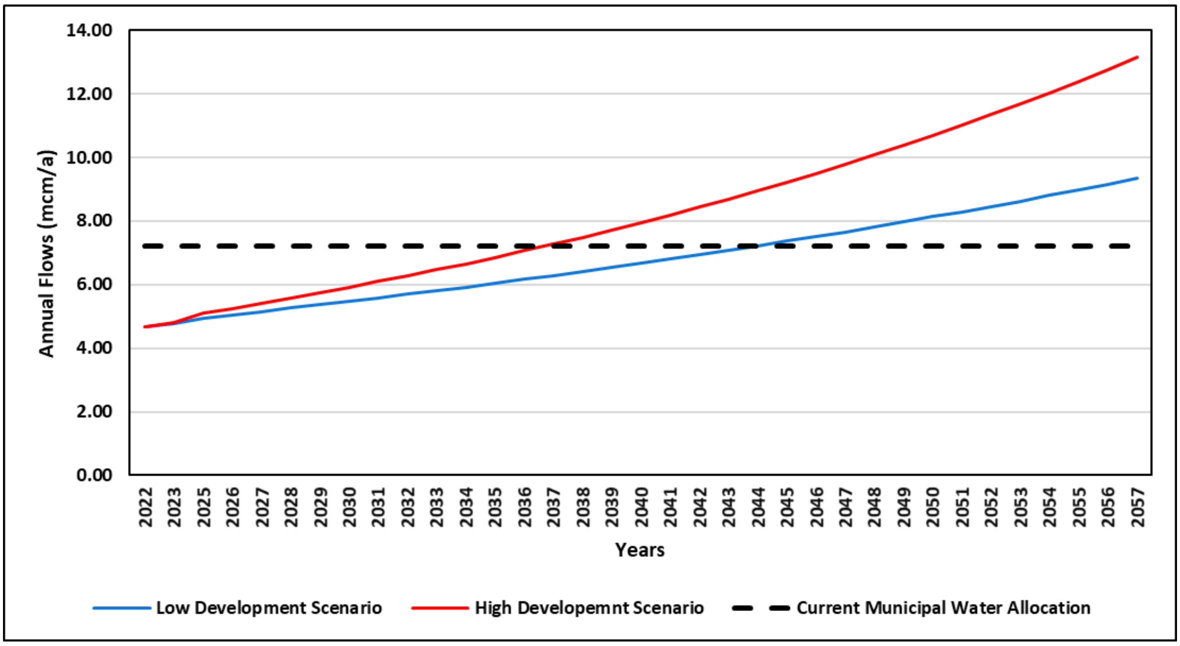

Figure 44: Municipal Water Allocation from the Eerste River and Development Scenarios

The return flows were projected to increase due to the development scenarios from 6.783 Mm^3/a (19 Ml/day) estimated for the year 2022 to 11.575 Mm^3/a (32 Ml/day) and 15.477 Mm^3/a (42 Ml/day) by 2057 in low and high development scenarios, respectively. These return flows were deemed to surpass the current treatment capacity of the Stellenbosch WWTW of 35 Ml/day in high development scenario in the year 2050, as presented in Figure 45. The projected return flows under the development scenarios are presented in Appendix H.

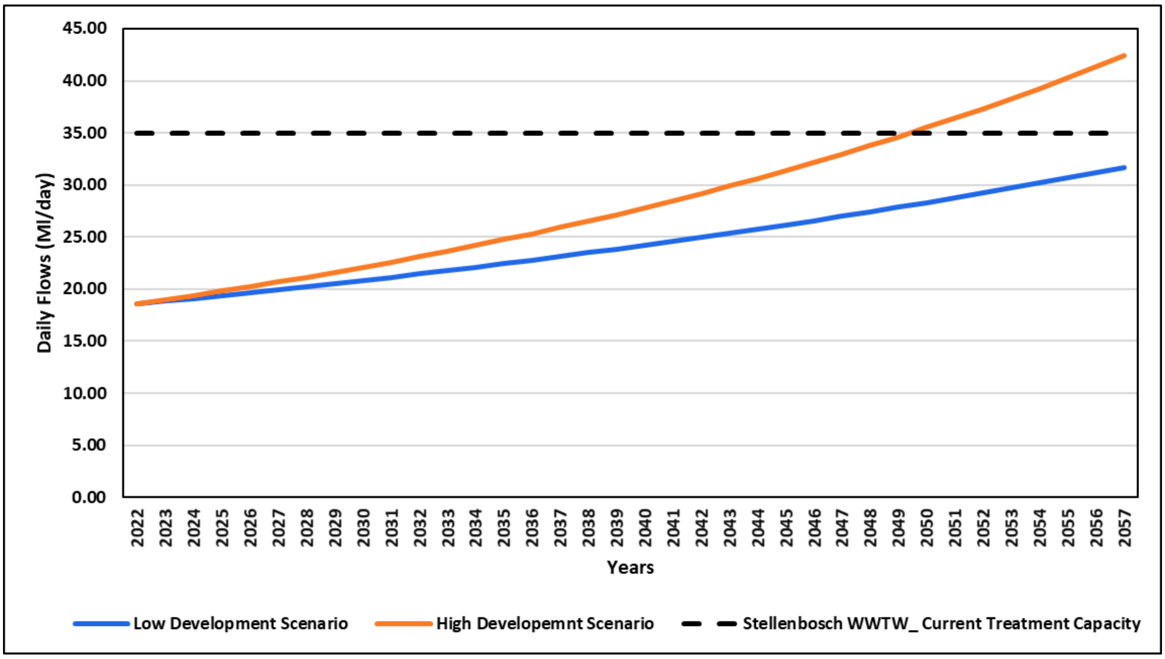

Figure 45: Return Flows and Development Scenarios

The impact of development scenarios on the Eerste River was determined based on the methodology highlighted in yellow in Figure 46.

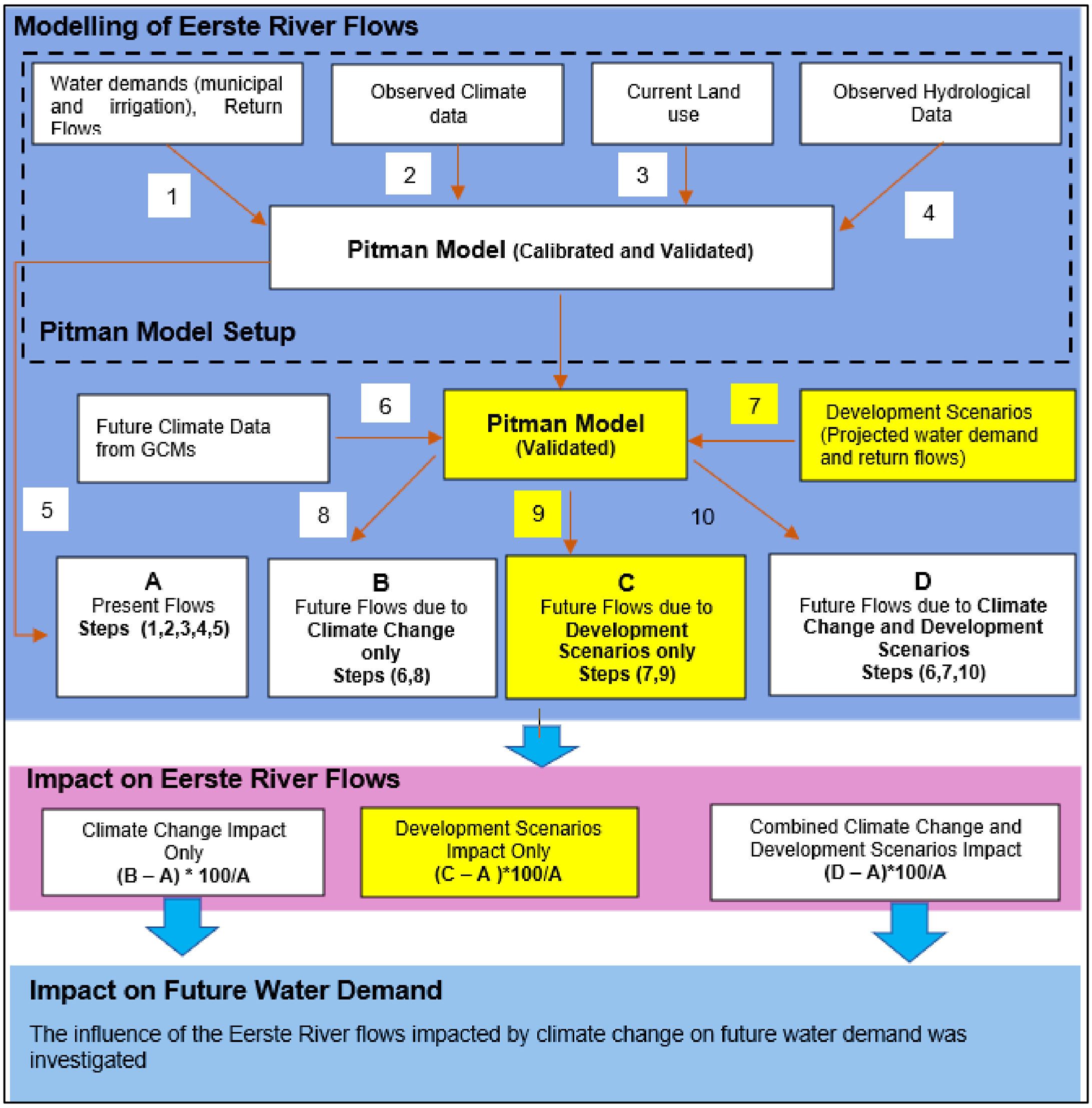

Figure 46: Methodology for Determining the Impact of Development Scenarios

The results on the change in the observed mean annual runoff at G2H037, G2H005, G2H020, and G2H040 in the near-future period relative to the present-day period are presented in Table 24.

Table 24: Impact of Development Scenarios on River Flows at Gauging Stations

Gauging Station	Low Development Scenario	High Development Scenario
	Change (%)	Change (%)
G2H037	-8.8	-13.5
G2H005	-0.1	-0.5
G2H020	-0.4	-0.6
G2H040	+9.4	+13.3

Table 24 shows that there could be a decrease in the mean annual runoff at the G2H037, G2H005, and G2H020 in the near-future period relative to the present-day period due to increase in the municipal water abstractions based on the development scenarios. This decrease in river flows was noted to be more pronounced at G2H037 gauging station than at G2H005 and G2H020 because of the higher percentage of change in the river flows in the low and high development scenarios.

It was also observed that the mean annual runoff at G2H040, which represented the flows at the outlet of the catchment, would increase in both low and high development scenarios, respectively, as presented in Table 24. The increased flows at G2H040 was determined with the Pitman model to be 61.9 Mm^3/a and 64 Mm^3/a in the low and high development scenarios, respectively. It was deemed that the increase in river flows could have emanated from the increase in the return flows from the Stellenbosch WWTW to the lower section of the Eerste River as a corresponding response to the increase of municipal water in the water supply network of the Stellenbosch Municipality. The impact of the development scenarios on the available water in catchments is presented in Table 25.

Table 25: Impact of Development Scenarios on Available Water in Catchments

Catchment	**Low Development Scenario**	**High Development Scenario**
	Change (%)	**Change (%)**
G22F	-15	- 20
G22G	0	0
G22H	+6	+9
Eerste River	- 2	- 3

Table 25 presents that the available water is expected to decrease in G22F and increase in G22H. However, the magnitude could be more in high development scenario than in the low development scenario. It is expected that the net impact on the available water in Eerste River Catchment could be a reduction in the river flows of 2% and 3% in low and high development scenarios, respectively, in the near-future period.

The comparison of the available water and municipal water abstractions based on the present-day abstraction pattern revealed that the reduction in available water in G22F quaternary catchment was more pronounced between the months of January to March and December to March across the hydrological year in low and high development scenarios, respectively. The seasonal trend of the municipal water abstractions and available water in G22F quaternary catchment is presented in Figure 47.

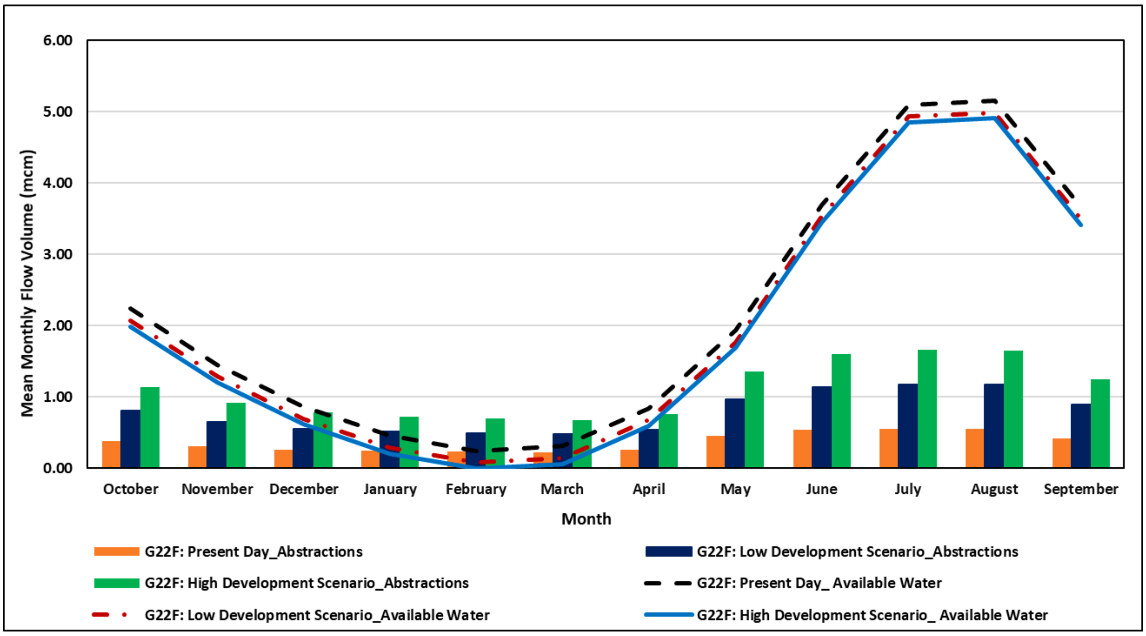

Figure 47: Available Water and Municipal Water Abstractions under Development Scenarios

Figure 47 illustrates that the lowest available water in G22F quaternary catchment due to the impact of development scenarios is expected to be in February. The reduction in available water is anticipated to be less between June and August relative to other months because the municipal water abstractions are expected to be less compared to available water.

The results also showed that there could be no additional impact on the available water due to irrigation demand under both development scenarios. This situation was observed to be the result of no change in irrigation demand in the near-future period compared to the present-day period.

6.1.4 Impact of Climate Change and Development Scenarios on Eerste River

The combined impact of climate change and development scenarios was determined by projecting that climate change and increase in municipal water requirements will occur at the same time in the 2022-2057 period. The changes in climate data due to the climate change signal determined by the RCP 4.5 and RCP 8.5 were assessed together with the increase in municipal water demand projected in the low and high development scenarios. No growth in irrigation water requirement based on the increase in the area of irrigated agriculture in the catchment was considered in the development scenarios as highlighted in Section 6.1.3.

The adopted methodology to determine the combined impact of climate change and development scenarios on the flow in the Eerste River is highlighted in yellow in Figure 48.

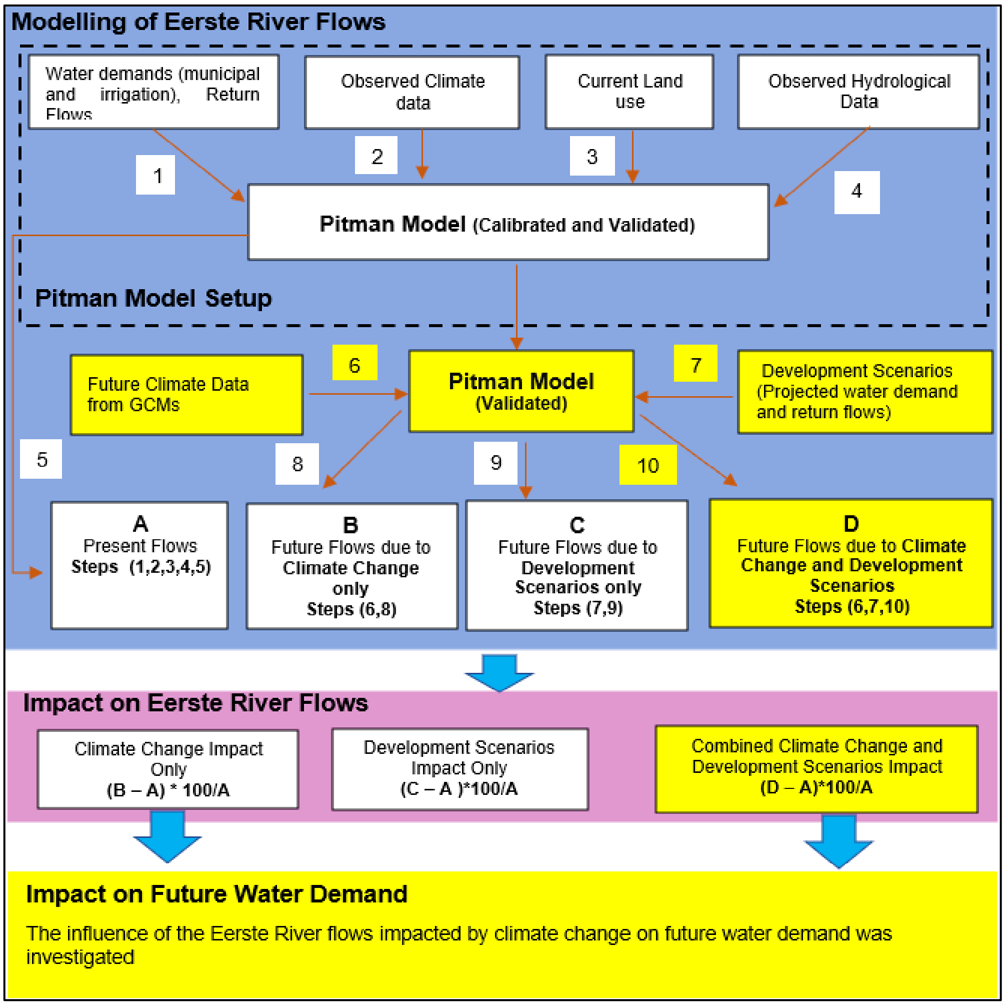

Figure 48: Methodology under Combined Climate Change and Development Scenarios

The results on the impact on mean annual runoff observed at the gauging stations determined by the methodology presented in Figure 48 are presented in Table 26.

Table 26: Impact of Climate Change and Development Scenarios at Gauging Stations

Gauging Station	Low Development Scenario Change %		High Development Scenario Change %	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
G2H037	-17.0	-16.0	-22.0	-21.0
G2H005	-2.0	-2.0	-3.0	-2.0
G2H020	-11.0	-10.0	-11.0	-11.0
G2H040	-3.0	-0.4	+2.0	+3.0

Table 26 presents that there will be a reduction in the mean annual runoff at G2H037, G2H005 and G2H020 due to the impact of climate change induced by the RCP 4.5 and RCP 8.5 in both low and high development scenarios. The reduction in flows was noted to be more pronounced on the observed flows at G2H037 than at the other stations.

It is expected that the river flows at the outlet of the Eerste River Catchment, which were modelled at G2H040, could increase and decrease under high and low development scenarios, respectively, coupled with climate change. The river flows at G2H040 were determined with the Pitman model to be 57.6 Mm^3/a and 58.6 Mm^3/a under RCP 4.5 and RCP 8.5, respectively, given a high development scenario. At the same time, the river flows at G2H040 were determined to be 55.2 Mm^3/a and 56.4 Mm^3/a under RCP 4.5 and RCP 8.5, respectively, given a low development scenario. The results indicated that there could be a reduction in the available water within the catchments, as presented in Table 27.

Table 27: Impact of Climate Change and Development Scenarios on Available Water

Catchment	Low Development Scenario Change (%)		High Development Scenario Change (%)	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
G22F	-25.2	-23.7	-30.2	-28.8
G22G	-13.0	-11.7	-13.0	-11.7
G22H	-1.6	-0.6	+1.5	+2.5
Eerste River	-11.7	-10.2	-11.9	-10.7

The results showed that the impact of development scenarios and climate change could cause a reduction in available water in the G22F quaternary catchment. It is expected that the reduction in available water in the G22F quaternary catchment will still not satisfy the expected municipal water abstractions based on the present-day abstraction pattern. In other words, the water volume to meet the municipal abstractions projected by development scenarios will be higher than the available water in the river. It will not even meet the municipal abstractions based on the present-day pattern. Figure 49 presents the seasonal variation of the available water and municipal water abstractions in G22F quaternary catchment due to RCP 4.5 and the development scenarios.

The inadequacy of the available water to meet the municipal water abstractions was more pronounced in December to March, and January to March in high and low development scenarios, respectively, as presented in Figure 49. The results also showed that the lowest available water in the G22F quaternary catchment could occur in February. This pattern of seasonal variation of municipal water abstractions and development scenarios in G22F quaternary catchment was also observed under the combined impact of climate change induced by RCP 8.5 and the development scenarios. However, the only difference was in the magnitude of change. For the sake of brevity, it will not be presented here.

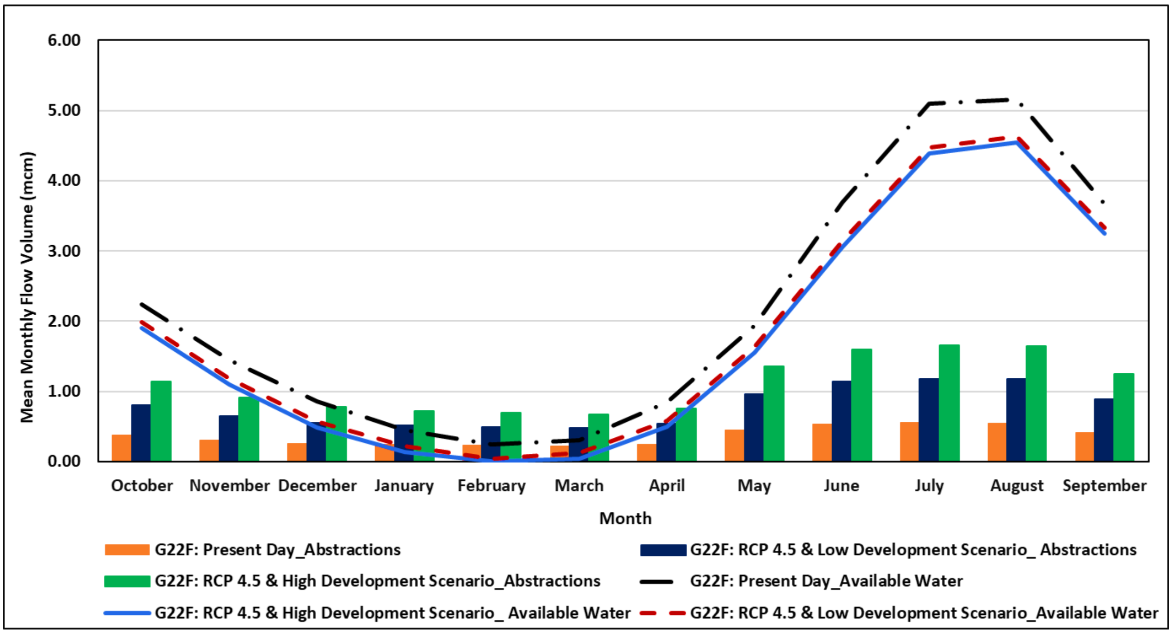

Figure 49: Available Water and Municipal Abstractions under RCP 4.5 & Development Scenarios

The results indicated that the irrigation demand is expected to increase by 12.1% and 11.7% in the Eerste River Catchment based on Equation 10, which was modelled to be 5.3 Mm^3/a and 5.1 Mm^3/a with the Pitman model under RCP 4.5 and RCP 8.5, respectively, coupled with development scenarios. The seasonal variation of irrigation demand and available water for the combined impact of climate change under RCP 4.5 and the development scenarios, is presented in Figure 50.

The increase in irrigation demand, specifically in the summer, was observed to have been triggered by climate change and not necessarily development scenarios. The reason is that the increase in irrigation demand was the same under low and high development scenarios, as presented in Figure 50. The results showed that the magnitude of increase in irrigation demand could be more pronounced in G22G and G22H quaternary catchments than in G22F quaternary catchment.

The pattern of seasonal variation of irrigation demand and available water in catchments as highlighted in Figure 50, was the same as for the impact of climate change influenced by RCP 8.5 coupled with development scenarios with the only difference being in the magnitude of change, and will not be presented for the sake of brevity.

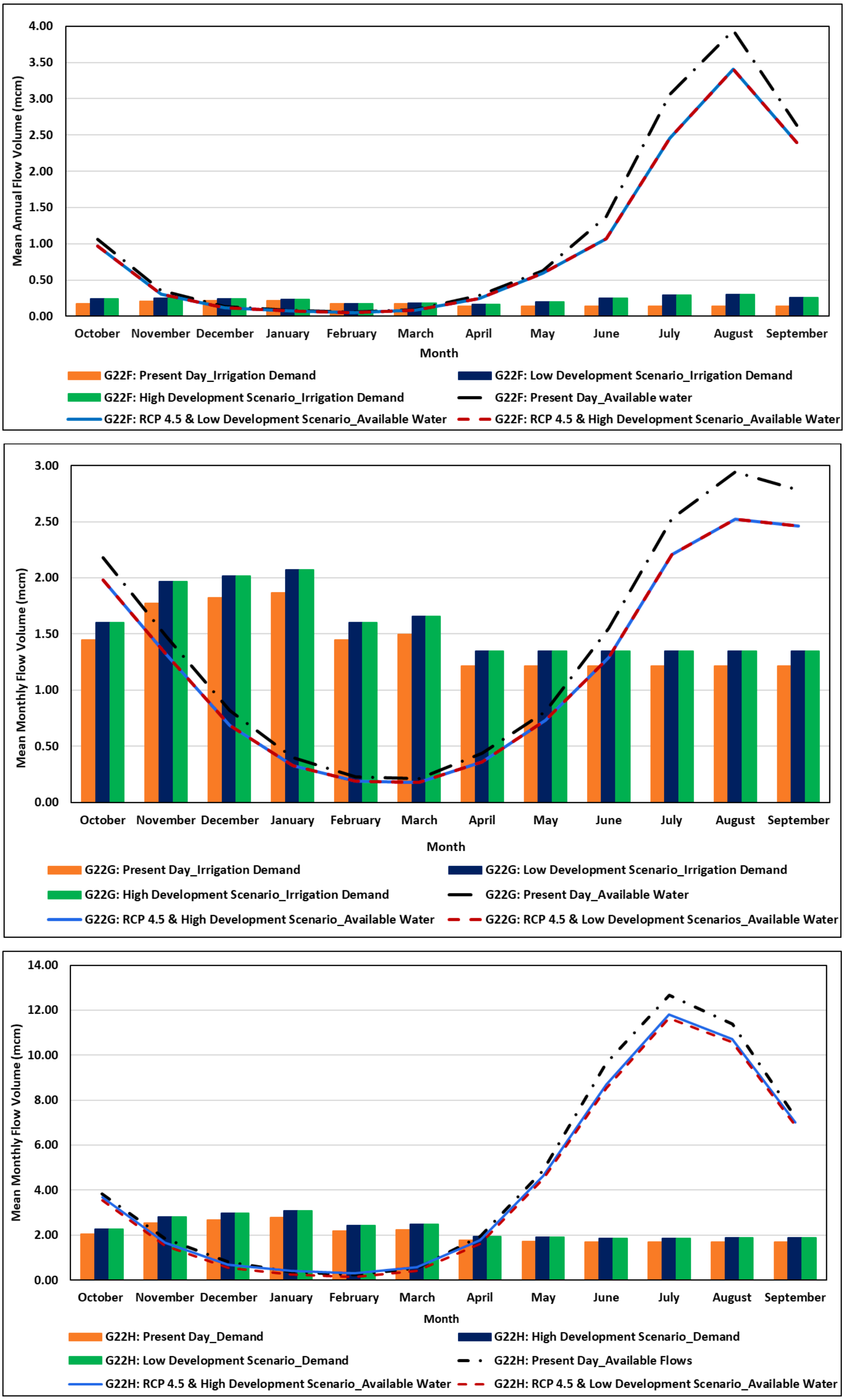

Figure 50: Available Water & Irrigation Demand under Climate Change & Development Scenarios

6.2 Discussion

This section presents a discussion of the results of this research.

6.2.1 Present-Day Eerste River Flows

The results on present-day Eerste River flows observed at G2H037, G2H020 and G2H040 were determined to be within the range of the criteria of goodness of fit, as presented in Section 6.1.1. At G2H005, only the standard deviation and the log of standard deviation criteria, which were -14.9% and -10%, respectively, were outside the recommended thresholds of 6%, as presented in Table 14. This difference in the standard deviation and log standard deviation values could be attributed to under-representation of the exact incremental catchment runoff between the Kleinplaas Dam and the G2H005 gauging station in the Pitman model.

Similar challenges in simulating the Eerste River flows at G2H005 were observed in the WR2012 study (Bailey & Pitman, 2016). In that study, the standard deviation and log standard deviation were determined to be -36% and -31.6%, respectively. The results of this research are, therefore, a significant improvement on the previous modelling exercise.

The modelled present-day Eerste River flows at the gauging stations can be deemed to be acceptable as there are no significant differences between the observed and simulated flows based on the goodness of fit criteria. The comparison of the naturalised flows determined in this research to those determined in previous studies undertaken in the Eerste River is presented in Table 28.

Table 28: Comparison of the Naturalised Flows

Quaternary Catchment	**1920 - 2004**	**1920-2009**	**1983-2018**
	WR2005 MAR (Mm^3)	WR2012 MAR (Mm^3)	This research MAR (Mm^3)
G22F	34.2	36.58	43.65
G22G	14.59	14.92	14.95
G22H	DWAF (2008a)		Present-day
	54		55.17

Table 28 indicates that there is an increase in naturalised flows in the Eerste River Catchment. This increasing trend in the naturalised flows in Eerste River can be attributed to the following observations:

- The extension of the G2C rain file between 2009-2018;
- The use of the SAMI Groundwater module in the Pitman model compared to the DWAF (2008a);
- The use of updated data for return flows from Stellenbosch WWTW and water abstractions from Eerste River by Stellenbosch Municipality;
- The use of updated land use and land cover data of the Eerste River Catchment; and
- The incorporation of the interbasin water transfer from WCWSS to Eerste River Catchment in the modelling of Eerste River.

The results in Figure 30 show that available water in the Eerste River Catchment is adequate to meet the municipal water abstractions of the Stellenbosch Municipality. However, on average the municipality does not utilise the capped water allocation of 7.224 Mm^3/a fully. There is a possibility that the water conservation and water demand measures that were introduced by the Stellenbosch Municipality due to the drought of 2015 (SM, 2017a), are partly contributing to the lower demand for municipal water. The adoption of this water demand management approach could have caused the average water abstractions to be less than the capped water allocation of 7.224 Mm^3/a. It is also possible that the population and socio-economic activities in the Stellenbosch Municipality did not increase as expected or projected to utilise the capped water allocation fully.

The availability of more water in winter season than in summer season, and oppositely for irrigation demand as shown in Figure 31, has emerged from the results to be the leading cause for the need for farm dams and interbasin water transfer from WCWSS to meet the irrigation water demand in Eerste River catchment. The conclusion made, therefore, is that the use of additional water resources apart from the Eerste River is of paramount importance to the agriculture sector in the catchment.

6.2.2 Impact of Climate Change on Eerste River

The general overview of the future climate suggests that there could be an increase in evaporation and a decrease in rainfall in the Eerste River Catchment. The results agree with New (2002), Steynor (2004) and Louw *et al*. (2012) whom all reported similar trends in the Western Cape in which Eerste River Catchment is located. It is anticipated that the magnitude of change of future rainfall could depend on the trajectory climate change would follow regarding the emission of the greenhouse gases in the atmosphere. If the climate change pattern would follow the pathway of RCP 8.5, it is expected that in the far-future period, there could be more decrease in rainfall than in the near-future period, and oppositely for RCP 4.5.

The trend of future rainfall could then be attributed to the inherent assumptions that emissions in RCP 8.5 will continue to rise to 2100 while under RCP 4.5, emissions will peak at 2040 then decline towards 2100 as reported by Meinshausen *et al*. (2011). The results in Figure 36 and Figure 37 indicate that there could be a shift in the occurrence of peak rainfall from the month of June to the month of July in the far-future period due to climate change. Nevertheless, the pattern of seasonal variation of rainfall between far-future and present-day periods would be the same.

The higher reduction in available water due to climate change anticipated in the far-future period under RCP 8.5 relative to RCP 4.5 (Table 23) is in agreement with results by Misgana (2018) and Wayne (2013). Both authors reported that towards 2100 the radiative concentration in the atmosphere would be more under RCP 8.5 than RCP 4.5. Therefore, the likelihood of having more reduction in available water under RCP 8.5 than RCP 4.5 in far-future period seems to be a plausible expectation. However, the slightly higher reduction in available water in the near-future period than the far-future period under RCP 4.5 could be attributed to a slightly higher reduction in rainfall in the former period than in the latter period.

The municipal water abstractions seem not to be affected significantly by the reduction in available water due to climate change. Failure to meet present-day water abstractions in February and March has been noted under RCP 8.5 in the far-future period (Figure 42). There is still a possibility that if the abstraction pattern is changed to have more abstractions during June to August to offset abstraction that occurs in February and March, the impact of the climate change could not be pronounced in the future periods under both RCP 4.5 and RCP 8.5. This suggestion requires assessment on the capacity of the Idas Valley Dams to establish the possibility of storing additional water in these dams.

Climate change is also expected to cause an increase in irrigation demand in future periods as shown in Figure 43. These results agree with the finding from Pengelly *et al*. (2017) which reported that climate change could increase irrigation demand by 2040 in Berg WMA, which includes the Eerste River Catchment. The comparison of the flows at the outlet of the catchment, which were modelled at G2H040, and irrigation demand, shows that the catchment has adequate water to meet the irrigation water demand even under climate change. Even though this is the case, the seasonal variation of available water and irrigation demand is still a challenge.

Increasing the capacity of the existing farm dams could assist in storing more water during the winter season which can be used during the summer season to meet the anticipated increase in the irrigation demand. The construction of new dams within the vicinity of the farms could reduce the available land for irrigated agriculture. This can be coupled with an increase in winter filing of dams as it is currently being practised. The increase of water requirements from interbasin water transfer through WCWSS to meet the irrigation demand seem to be a challenging option because the system is already committed, as reported by Pengelly *et al.* (2017).

The overview of the impact of climate change on irrigation demand and municipal abstractions aligns with those of the Steynor (2004) study. The study reported that the impact of climate change in Western Cape is expected to be more on irrigation demand than on the municipal water abstractions. The results do not agree with Pengelly *et al*. (2017) findings which projected the opposite in Berg WMA. It can be deemed that Pengelly *et al*. (2017) dealt with water supplied by WCWSS, which is used more for municipal than irrigation activities. This projection could have resulted in concluding that the impact of climate change could be more on the water for municipal use than irrigation.

6.2.3 Impact of Development Scenarios on Eerste River

The development scenarios project an increase in both municipal water abstraction and return flows in the Eerste River Catchment with a reduction in available water in the catchment. The significant impact of the different development scenarios is expected in the area upstream of Kleinplaas Dam due to the position of the intake weir of Stellenbosch Municipality as shown by a higher reduction in river flows at G2H037 compared to other gauging stations in Table 24. The reduction in available water could affect the contribution of water from Eerste River in meeting the water demand of the City of Cape Town because most of the water from upstream of the Kleinplaas Dam is diverted at the dam to meet the water demand of the City of Cape Town. There is a strong need to promote water conservation and water demand management practices as one of the best ways of limiting the increase in municipal water abstractions.

The minimal change in the flows propagating downstream of the Kleinplaas Dam as observed at G2H005 and G2H020 (Table 24), and no discernible impact of irrigation demand on the available water, indicates that different development scenarios could not cause a significant reduction on the flows in the Eerste River downstream of the dam. This notion requires continuous use of farm dams and water from WCWSS to supplement the irrigation demand.

The development scenarios also provide an opportunity for water trade-off in a way that the water to Wynland WUA from WCWSS can be traded off with increased return flows. This trade-off could allow farmers within the Wynland WUA to use the increased return flows from the Stellenbosch WWTW for irrigation. At the same time, the water that was supplied to Wynland WUA from WCWSS can be used to compensate the reduction in the available water contributed from Eerste River to meet the water demand of the City of Cape Town at the Kleinplaas Dam. This suggestion agrees with SM (2017a; 2018) studies that reported that return flows are potential alternatives to meet irrigation demand in Stellenbosch Municipality. There is a need for further investigation on the implementation of this trade-off especially to ascertain if the water quality of return flows is acceptable for irrigation use.

6.2.4 Impact of Climate Change and Development Scenarios on Eerste River

The combined impact of climate change and the development scenarios on the flows of the Eerste River seem to exacerbate the independent impact of climate change and development scenarios in the near-future period based on comparison of results in Table 27, Table 23 and Table 25, respectively. Development scenarios are expected to have more influence on the reduction of the available water for municipal water use, because under the impact of climate change only, the available water was adequate to meet the municipal water abstractions in the near-future period as presented in Figure 49 and Figure 41, respectively.

The results in Table 26 shows that the influence of the development scenarios tends to be more noticeable in the increase of the return flows under the high development scenario due to increase in river flows modelled at G2H040. In contrast, under the low development scenario, the impact of climate change prevails because of the reduction of river flows at the same gauging station.

On the other hand, the increase in irrigation demand is driven by the climate change scenarios considering that under development scenarios only, an increase in irrigation demand was not observed. Increasing the capacity of existing farm dams and the promotion of water conservation and water demand management practices could assist in meeting the increase in water demand.

The results in Table 27 indicates that the trajectory of the climate change scenarios is more significant compared to that of development scenarios because the impact on Eerste River flows is almost similar for each RCP regardless of the development scenario coupled with it. It can, therefore, be concluded that climate change would be the determining factor of the combining impact of climate change and development scenarios in the near-future period.

6.3 Summary

A summary of the impact of climate change and development scenarios on the Eerste River is presented in Table 29.

Table 29: Impact of Climate Change and Development Scenarios on the Eerste River

Present Day Period		Climate Change		Development Scenarios	Climate change and Development Scenarios
		Near Future Period	Far-Future Period	Near-Future Period	Near-Future Period
Eerste River Flows					
Catchment	**Mm^3/a**	**%** (relative change)			
G22F	39.68	-9 to -10	-10 to -20	-15 to -20	-24 to -30
G22G	16.38	-12 to -13	-13 to -25	0	-12 to -13
G22H	55.42	-7 to -8	-8 to -15	+6 to +9	-1 to +3
Eerste	**111.48**	**-8 to -9**	**-9 to -18**	**-2 to -3**	**-10 to -12**
Water Demand					
Type	**Mm^3/a**	**%** (relative change)			
Municipal	7.224	0	0	+30 to +82	+30 to +82
Irrigation	44	+12	+17 to +29	0	+12

Table 29 presents that the impact of the climate change on the Eerste River is expected to be more significant compared to the impact of development scenarios in the future periods relative to present-day period. Based on the results, it has been concluded that the most significant impact of climate change and development scenarios on the Eerste River would be a reduction in river flows of between 2% and 18%. It should be noted that the municipal demand in Table 29 has been represented by capped water allocation for municipal water abstractions in Eerste River.

7. Conclusion

This research was aimed at determining the impact of climate change and different development scenarios on the flow of the Eerste River, using hydrological modelling. The research was focused on understanding the present-day naturalised flows in the Eerste River to which the impact of climate change and development scenarios was then determined. The river flows impacted by climate change were further investigated to determine the changes that could arise in the irrigation and municipal water demand. The literature was reviewed on the theories and methods of climate change, development scenarios and hydrological modelling that was then used to determine the methodology of the research.

The Pitman model and three modelling periods denoted as present-day (1983-2018), near-future (2022-2057) and far-future (2058-2093) were used to model the impact of climate change and development scenarios on the Eerste River. The Pitman model was configured with land use and land cover, water demand, hydrological and climate data that was collected from different sources. The future climate data which was used for investigation of the impact of climate change was based on climate outputs from 11 GCMs of CMIP5, which were enforced by RCP 4.5 and RCP 8.5. This data was first analysed before being utilised in the Pitman model. The modelling was done in three phases to investigate a) impact of climate change only, b) impact of development scenarios only, and c) combined impact of climate change and development scenarios.

The research has shown that the Pitman model can represent the present-day naturalised flows in the Eerste River based on the comparison of the observed and simulated flows at the gauging stations. It was found that the naturalised flows, which were regarded as available water in the catchment, are inadequate in meeting the irrigation demand, especially in the summer season

The research has confirmed the existence of farm dams and the need for water from the Western Cape Water Supply System to supplement the available water in the Eerste River in meeting the irrigation demand. It has been concluded that the Eerste River has adequate water to meet the seasonal distribution of municipal water abstractions.

The research has shown that climate change is expected to cause evaporation to increase by 6% to 15% in future periods. At the same time, rainfall is anticipated to decrease by 2% to 8%. Based on this future climate, there is a possibility that the occurrence of highest rainfall could shift from June to July in the Eerste River Catchment in the far-future period. The seasonal rainfall pattern in the future periods is expected to be the same as in the present-day period.

The employment of future climate data in the Pitman model has revealed that available water in the Eerste River Catchment is expected to decrease by 8% to 18% and trigger a potential increase in irrigation demand of 12% to 29% in future periods with the expectation that municipal water abstractions could not be met, especially in February and March in the far-future period. The increase in irrigation demand and failure to meet the municipal water abstraction is expected to be worsened by the seasonal distribution of the available water and the water demand. This projection is based on the observation that total annual irrigation demand in the catchment was determined to be lower than the available water at the outlet of the catchment.

The research has suggested that an increase in capacity and promotion of the winter filling of the existing farm dams could be a viable option to meet the potential increase in irrigation demand. The feasibility of increased water storage in farm dams should be investigated further, including the effects of increased evaporation, seepage & other losses from such dams over the summer period.

The research has also suggested shifting of the municipal water abstractions between February and March based on the present-day abstraction pattern to the period between June and August. This adjustment of municipal water abstraction pattern could cause the available water in the Eerste River to be adequate to meet the municipal water abstractions in the future periods. This notion requires investigation of the reservoir capacities of Idas Valley Dams to accommodate the additional water in June and August, as well as investigation of the ecological water requirements regarding the changed monthly flow regimes.

The impact of development scenarios on the Eerste River is expected to cause possible reduction of the available water of between 15% to 20% especially upstream of the Kleinplaas Dam due to the increase of municipal water abstractions of between 30% to 82% above the current capped water allocation of 7.224 Mm^3/a. It is envisaged that municipal water abstractions and not necessarily irrigation demand could cause a reduction in available water of the river in the near-future period. This anticipation assumes continuous use of farm dams and water from WCWSS to supplement the irrigation demand, as failure to do so, could worsen reduction of the available water due to unmet irrigation demand.

The research has also established increase in the return flows of 9.4% to 13.3% from the Stellenbosch WWTW to the lower section of Eerste River, which is expected to surpass the current treatment capacity of 35 Ml/day by the year 2050 in the high development scenario.

The increase in return flows is expected to be a corresponding response to the increase in municipal water abstractions in the water supply system of Stellenbosch Municipality which could result in a net reduction of available water in the catchment of between 2% to 3%. It has been concluded that the development scenarios are expected to reduce the contribution of available water from Eerste River to meet the water demand of the City of Cape Town. The reason is that most of the water upstream of the Kleinplaas Dam that remain in the river after satisfying municipal water abstractions is diverted at the dam to the City of Cape Town.

The research has also revealed that there is an opportunity that additional water from return flows in the lower section of the Eerste River could be traded off with water from WCWSS to Wynland WUA for irrigation use. This trade-off could allow water from WCWSS to Wynland WUA to compensate for the reduction in available water contributed from Eerste River to the City of Cape Town at Kleinplaas Dam. However, this will require further investigation on the modalities of the trade-off, and water quality aspects.

Additionally, the research has found that the combined impact of climate change and development scenarios could cause a general decrease of between 10% to 12% on the available water in the Eerste River in the near-future period. At the same time, this combined impact could cause a potential increase in irrigation demand of 12% in the summer season. This situation would result in a reduction in the contribution of available water from Eerste River diverted at the Kleinplaas Dam to meet the water demand of the City of Cape Town. The river flows at the outlet of the catchment are expected to change between -3% and +3% with the contribution of increased return flows caused by the development scenarios. Promotion of water conservation and water demand management practices and increasing the capacity of existing farm dams could assist in curbing the increase in water demand. It should be noted, that such recommendations should be implemented sooner rather than later, regardless of whether or not the climate change scenarios materialize fully.

This research has established that the overall impact of climate change and development scenarios would be a reduction in available water of between 2% and 18%. Climate change is expected to cause a significant reduction of available water in the Eerste River compared to the development scenarios. This reduction in available water could worsen failure to meet the potential increase in irrigation demand and need for more water to meet the municipal water abstractions in the future periods. Therefore, there is need to factor in the impacts of climate change and development scenarios on the Eerste River, with much emphasis on the impacts of climate change, in the water resources planning of the Stellenbosch Municipality and Wynland WUA.

8. Recommendations

This chapter recommends areas of further research on the Eerste River based on the findings of this research. This research has shown that there is a possibility of a potential increase in irrigation demand due to the impact of climate change. Grapes were adopted as the crops that are currently being used for irrigated agriculture in the Eerste River Catchment. This research, therefore, recommends investigation on the viability of replacing the grapes with an alternative commercial crop that has fewer water requirements and equal or better markets than the grapes to reduce the expected potential future irrigation demand.

This research also recommends the investigation on the impacts of the changing land use and land cover on the Eerste River. This recommendation emanates from the understanding that although future land use and land cover was assumed to be constant, there could be a possibility that it might change in the future. A change in land use and land cover could exacerbate the impact of climate change and development scenarios that has been determined in this research.

Undertaking the above recommendations could further assist in the water resources planning of the Eerste River, considering its importance in contributing to the socio-economic activities of Stellenbosch Municipality and South Africa at large.

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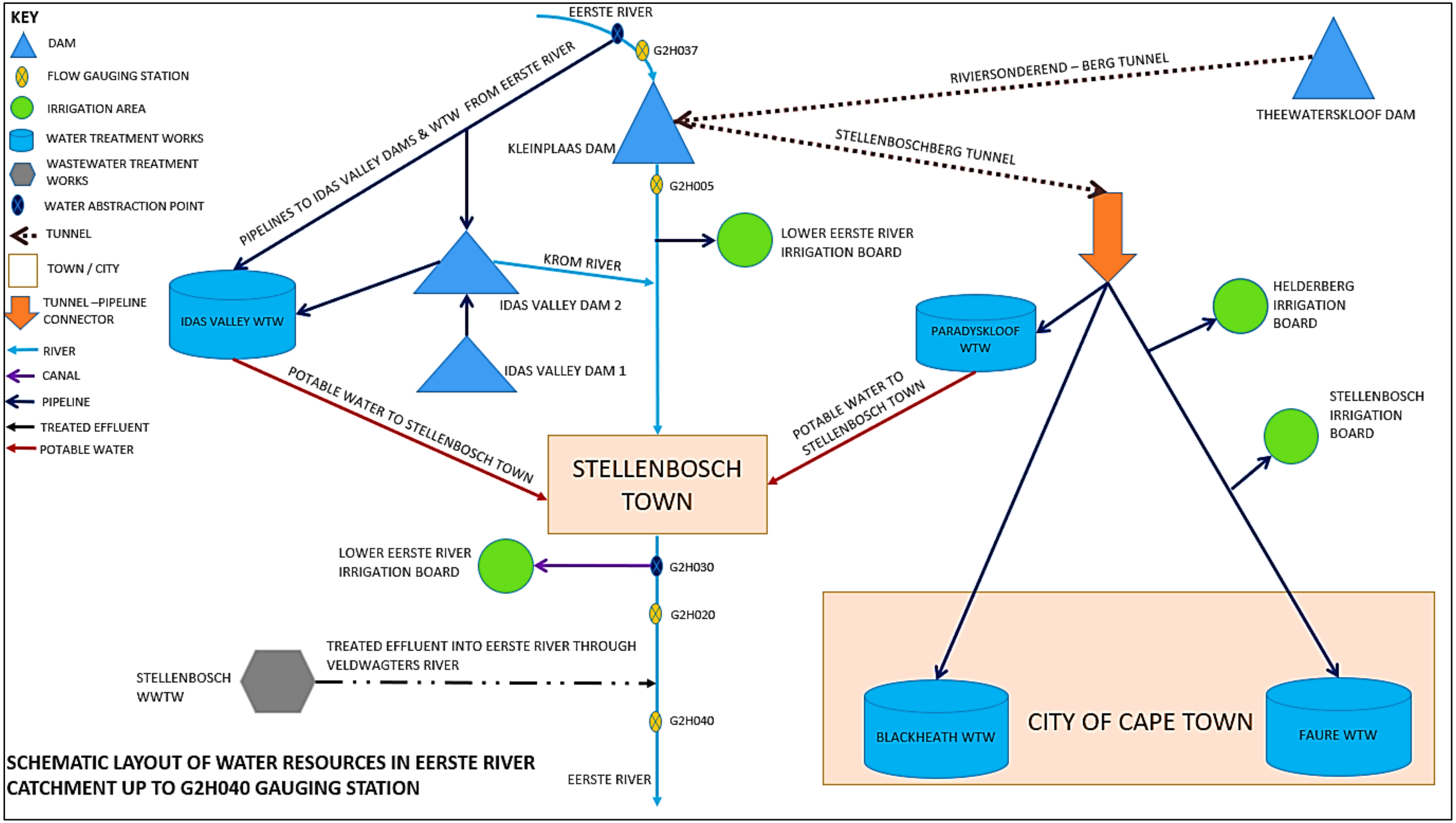
Appendices

Appendix A: G2H005 Streamflow Data for Present-Day Period

1982	1.68	0.62	1.09	0.49	0.55	0.51	0.32	7.89	8.24	8.98	2.66	3.29
1983	0.75	0.37	0.40	0.36	0.30	0.31	0.35	5.04	1.15	6.34	2.05	4.66
1984	3.68	0.29	1.13	0.37	0.83	1.28	0.81	1.38	7.77	6.72	4.68	2.26
1985	0.54	0.29	0.56	0.54	0.26	0.50	1.11	1.58	4.75	5.14	11.30	6.58
1986	0.16	0.28	0.54	0.63	0.31	0.22	0.20	3.51	3.14	4.04	4.61	2.13
1987	0.59	0.23	0.50	0.43	0.52	0.50	0.49	1.09	1.49	4.63	3.05	2.38
1988	0.19	0.21	0.66	0.91	0.89	1.75	0.40	1.71	1.76	3.09	3.81	2.34
1989	0.45	0.61	0.71	1.20	0.86	0.50	3.49	2.62	3.30	8.09	2.34	0.15
1990	0.46	0.34	1.13	1.13	0.91	0.75	0.21	2.67	4.34	6.52	4.24	4.45
1991	0.26	0.19	0.58	1.03	0.80	0.46	2.52	1.31	8.18	4.04	4.15	2.29
1992	1.44	0.19	0.41	1.20	0.84	0.36	4.06	4.65	4.03	13.20	5.10	1.02
1993	0.17	0.21	0.88	1.51	0.71	0.99	0.99	1.37	8.62	3.24	0.87	0.17
1994	0.42	0.32	0.38	0.97	0.45	0.73	0.34	0.80	1.38	4.85	4.30	0.23
1995	1.27	0.38	0.39	0.30	0.51	0.40	0.35	0.17	0.78	1.91	0.94	2.97
1996	3.46	0.90	0.91	0.26	0.38	0.43	0.49	1.15	3.01	0.43	2.06	0.25
1997	0.17	4.36+	0.18	0.39	0.37	0.40	0.33	4.32	1.19	2.00	0.70	0.22
1998	0.24	0.88	0.16	0.51	0.47	0.54	0.61	0.39	1.84	2.44	2.28	3.05
1999	0.21	0.17	0.57	0.81	0.36	0.52	0.52	2.73	0.26	2.03	1.11	2.01
2000	0.21	0.22	0.53	0.68	0.58	0.97	0.50	0.82	0.59	10.50	4.59	2.10
2001	0.21	0.21	0.41	1.39	0.31	0.54	0.56	1.60	2.20	3.09	3.29	0.19
2002	0.34	0.18	0.39	0.61	0.65	1.16	0.12	0.12	0.18	0.12	2.23	1.80
2003	0.60	0.18	0.51	0.64	0.70	0.61	0.90	0.08	0.65	0.79	5.17	0.88
2004	0.24	0.12	0.43	0.58	0.50	0.69	0.51	1.82	7.18	4.33	7.74	1.32
2005	0.14	0.12	0.52	0.85	0.81	0.90	0.81	1.57	0.89	1.83	4.92	0.21
2006	0.14	0.13	0.52	0.62	0.61	0.56	1.03	1.95	1.69	6.21	3.63	0.68
2007	0.76	1.13	0.15	0.51	0.47	0.58	0.61	1.25	1.57	4.63	0.92	2.73
2008	0.35	2.45	0.60	0.63	0.53	0.60	0.29	0.94	5.55	2.36	1.37	1.41
2009	0.40	2.93	0.40	0.69	0.69	1.11	0.48	2.65	1.47	1.70	1.04	0.17
2010	0.53	0.15	0.53	0.79	0.73	0.82	0.66	0.93	1.77	1.14	0.24	0.48
2011	0.14	0.12	0.65	0.73	0.70	0.74	0.64	0.38	2.23	2.66	6.69	1.08
2012	0.80	0.19	0.54	0.58	0.55	0.61	1.06	0.21	1.65	2.03	5.71	2.15
2013	0.21	2.63+	0.45	0.71	0.59	0.68	0.81	1.17	2.96	0.71	1.10	0.63
2014	0.21	0.60	0.60	0.59	0.54	0.65	0.56	0.39	1.07	1.92	0.29	0.18
2015	0.15	0.46	0.61	0.65	0.70	0.67	0.87	0.21	1.77	1.88	0.46	0.16
2016	0.13	0.24	0.42	0.39	0.32	0.43	0.17	0.06	0.65	0.17	0.43	0.30
2017	0.10	0.09	0.22	0.46	0.27	0.32	0.36	0.41	4.95	4.10	1.69	5.49

NB: Streamflow in million cubic meters starting from October to September in each hydrological year

Appendix B: Schematic Layout of Water Resources in Eerste River Catchment



Appendix C: Calibration Parameters in Pitman Model

Parameter		Effect on the simulated flow of increasing parameter			Lower Limit	Upper Limit
Name	**Description**	**MAR**	**SD**	**SI**		
ZMAX	Determines (in conjunction with ZMIN) the average infiltration to soil moisture	Down	Down	Down	0	1500
PI	Interception storage	Down	Up	Up	1	10
TL	Lag of surface runoff and subsurface flow from the upper zone of groundwater	No	No	Down	0	1
SL	Soil moisture level below which all subsurface flow ceases.	Down	Up	Up	1	3
ST	Moisture holding capacity of soil	Down	Down	Down	50	1000
FT	Maximum rate of subsurface flow at soil moisture capacity	Up	Down	Down	0	100
GW	Splits soil moisture into upper and lower (If GW=0 there is only an upper zone.)	No	Down (slightly)	Down	0	< = FT
ZMIN	Minimum rainfall intensity required to initiate surface runoff. Below this intensity all rainfall absorbed by soil	Down	Up	Up	0	150
POW	Determines rate at which subsurface flow (interflow plus groundwater) reduces as soil moisture is depleted	Down	Up	Up	1	3
GL	Lag of subsurface flow in the lower zone	No	Down (slightly)	Down	0	12
R	Controls rate at which evaporation reduces as soil moisture is depleted	Up	-	Down	0	1
GPOW	Groundwater calibration parameter	Down	Down	Up	1	3
HGSL	Groundwater calibration parameter	Down	Down	Up	0	5% to 20% of ST
HGGW	Groundwater calibration parameter	Up	Up	Down	1	About 10

Appendix D: Modelling Data for Calibration of Eerste River in the Pitman Model

PITMAN MODEL: MODELLING DATA FOR EERSTE RIVER CATCHMENT														
G2H005-G22F SUB-CATCHMENT														
		Year	**1983**	**1990**	**2009**	**2018**								
1	**Irrigation**	Farm Dams (km^2)	0	0	0	0								
		River (km^2)	0	0	0	0								
2	**Alien Vegetation (km^2)**		0	0	0	0								
3	**Afforestation (km^2)**		2.7	4.4	1.1	1.2								
4	**Farm Dams**	Volume (Mm^3)	0	0	0	0								
		Area (km^2)	0	0	0	0								
		Area / Capacity Equation Coefficients	a	NA										
			b	NA										
5	**Evaporation (mm)**	S-Pan	127	177	209	214	180	158	98	57	44	48	57	83
		A-Pan	159	222	261	268	226	197	123	71	55	60	71	104
6	**MAP (mm)**	1629												
7	**Catchment Area (km^2)**	31												
8	**Pitman Calibration Parameters**	**POW**	**GPOW**	**SL**	**HGSL**	**ST**	**FT**	**HGGW**	**ZMIN**	**ZMAX**	**PI**	**TL**	**R**	
		2	2	0	0	354	80	2	18	500	1.5	0.4	0	

G2H020-G22F SUB-CATCHMENT														
		Year	**1983**	**1990**	**2009**	**2018**								
1	**Irrigation**	Farm Dams (km^2)	1.17	1.34	2.8	2.8								
		River (km^2)	0.5	0.58	0.2	0.2								
2	**Alien Vegetation (km^2)**		0	1.8	1.8	0								
3	**Afforestation (km^2)**		3.4	5.7	3.8	4.3								
4	**Farm Dams**	Volume (Mm^3)	0.03	0.03	0.03	0.05								
		Area (km^2)	0.10	0.10	0.10	0.13								
		Area / Capacity Equation Coefficients	a	0.624										
			b	0.508										
5	**Evaporation (mm)**	S-Pan	127	177	209	214	180	158	98	57	44	48	57	83
		A-Pan	159	222	261	268	226	197	123	71	55	60	71	104
6	**MAP (mm)**	1310												
7	**Catchment Area (km^2)**	33												
8	**Pitman Calibration Parameters**	**POW**	**GPOW**	**SL**	**HGSL**	**ST**	**FT**	**HGGW**	**ZMIN**	**ZMAX**	**PI**	**TL**	**R**	
		2	2	0	0	520	3	2	75	600	1.5	0.4	0	

G2H020-G22G SUB-CATCHMENT														
		Year	**1983**	**1992**	**2009**	**2018**								
1	**Irrigation**	WCWSS_Pipeline (km^2)	0	8	10	10.00								
		Farm Dams (km^2)	20.83	12.83	30	30.90								
		River (km^2)	3.7	3.7	6.6	6.6								
		Year	**1983**	**1990**	**2009**	**2018**								
2	**Alien Vegetation (km^2)**		0	0	0	0								
3	**Afforestation (km^2)**		6.00	6.70	11.10	14.30								
4	**Farm Dams**	Volume (Mm^3)	10.00	10.00	12.10	16.10								
		Area (km^2)	2.01	2.01	2.20	2.56								
		Area / Capacity Equation Coefficients	a	0.624										
			b	0.508										
5	**Evaporation (mm)**	S-Pan	128	178	209	215	181	158	98	57	44	48	57	83
		A-Pan	160	223	262	269	227	198	123	71	55	61	71	105
6	**MAP (mm)**	785												
7	**Catchment Area (km^2)**	106												
8	**Pitman Calibration Parameters**	**POW**	**GPOW**	**SL**	**HGSL**	**ST**	**FT**	**HGGW**	**ZMIN**	**ZMAX**	**PI**	**TL**	**R**	
		2	2	0	0	420	35	2	50	600	1.5	0.25	0	

G2H020-G22H SUB-CATCHMENT														
		Year	**1983**	**1990**	**2009**	**2018**								
1	**Irrigation**	Farm Dams (km^2)	0.7	0.7	0.7	0.7								
		River (km^2)	0.8	0.8	0.8	0.8								
2	**Alien Vegetation (km^2)**		0	0	0	0								
3	**Afforestation (km^2)**		0.00	0.60	0.60	0.60								
4	**Farm Dams**	Volume (Mm^3)	0.03	0.03	0.03	0.03								
		Area (km^2)	0.10	0.10	0.10	0.10								
		Area / Capacity Equation Coefficients	a	0.624										
			b	0.508										
5	**Evaporation (mm)**	S-Pan	124	173	204	209	179	154	96	55	43	47	55	81
		A-Pan	155	216	255	261	220	192	120	69	53	59	69	101
6	**MAP (mm)**	815												
7	**Catchment Area (km^2)**	8												
8	**Pitman Calibration Parameters**	**POW**	**GPOW**	**SL**	**HGSL**	**ST**	**FT**	**HGGW**	**ZMIN**	**ZMAX**	**PI**	**TL**	**R**	
		2	2	0	0	350	8	2	90	600	1.5	0.25	0	

G2H040-G22H SUB-CATCHMENT														
		Year	**1983**	**1992**	**2009**	**2018**								
1	**Irrigation**	WCWSS_Pipeline (km^2)	0	10	35	35.00								
		Farm Dams (km^2)	21.25	10	25	26.8								
		River (km^2)	3.75	4.75	5	5								
		Year	**1983**	**1990**	**2009**	**2018**								
2	**Alien Vegetation (km^2)**		0	0.6	0.6	0								
3	**Afforestation (km^2)**		6.30	6.30	6.30	2.80								
4	**Farm Dams**	Volume (Mm^3)	11.09	11.43	12.83	12.83								
		Area (km^2)	2.77	2.80	2.95	2.95								
		Area / Capacity Equation Coefficients	a	0.960										
			b	0.440										
5	**Evaporation (mm)**	S-Pan	124	173	204	209	179	154	96	55	43	47	55	81
		A-Pan	155	216	255	261	220	192	120	69	53	59	69	101
6	**MAP (mm)**	815												
7	**Catchment Area (km^2)**	143												
8	**Pitman Calibration Parameters**	**POW**	**GPOW**	**SL**	**HGSL**	**ST**	**FT**	**HGGW**	**ZMIN**	**ZMAX**	**PI**	**TL**	**R**	
		2	2	0	0	110	85	2	0	370	1.5	0.25	0	

Appendix E: Climate Change induced Evaporation Data

RCP 4.5

RCP 4.5: S-PAN Evaporation for 2022-2057 Period (mm)											
G22F Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
134	189	220	225	189	166	104	60	46	50	60	88
G22G Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
135	190	220	227	190	166	104	60	46	50	60	88
G22H Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
131	184	215	220	188	162	102	58	45	49	58	86

RCP 4.5: A-PAN Evaporation for 2022-2057 Period (mm)											
G22F Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
168	237	275	282	237	207	131	75	58	63	75	110
G22G Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
169	238	276	283	238	208	131	75	58	64	75	111
G22H Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
164	230	269	275	231	202	127	73	56	62	73	107

RCP 4.5: S-PAN Evaporation for 2058-2093 Period (mm)											
G22F Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
138	194	226	231	193	169	105	62	48	52	63	91
G22G Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
139	195	226	232	194	169	105	62	48	52	63	91
G22H Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
135	190	220	226	192	165	103	60	47	51	61	89

RCP 4.5: A-PAN Evaporation for 2058-2093 Period (mm)											
G22F Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
173	243	282	289	242	211	132	77	60	65	78	114
G22G Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
174	244	283	290	243	212	132	77	60	66	78	115
G22H Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
169	237	275	282	235	205	129	75	58	64	76	110

RCP 8.5

RCP 8.5: S-PAN Evaporation for 2022-2057 Period (mm)											
G22F Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
135	189	222	227	192	168	105	60	47	51	61	89
G22G Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
136	190	222	228	193	168	105	60	47	51	61	89
G22H Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
132	185	217	222	190	163	102	58	46	50	59	87

RCP 8.5: A-PAN Evaporation for 2022-2057 Period (mm)											
G22F Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
169	237	277	284	240	209	131	75	59	64	76	111
G22G Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
170	238	278	285	242	210	131	75	59	65	76	112
G22H Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
165	231	271	277	234	204	128	73	57	63	74	108

RCP 8.5: S-PAN Evaporation for 2058-2093 Period (mm)											
G22F Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
147	206	239	243	203	178	113	66	51	55	66	96
G22G Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
148	207	239	244	204	178	113	66	51	55	66	96
G22H Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
144	201	234	238	202	174	111	64	50	54	64	94

RCP 8.5: A-PAN Evaporation for 2058-2093 Period (mm)											
G22F Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
184	258	299	305	255	222	142	82	64	69	82	121
G22G Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
186	259	300	306	256	223	142	82	64	70	82	122
G22H Quaternary Catchment											
October	November	December	January	February	March	April	May	June	July	August	September
180	251	292	297	248	217	138	80	61	68	80	117

Appendix F: Climate Change induced Precipitation Data

RCP 4.5

RCP 4.5: Precipitation Data for 2022-2057 Period (% of MAP)												
Year	October	November	December	January	February	March	April	May	June	July	August	September
2022	6.02	5.43	6.76	1.59	9.52	6.29	2.65	26.47	20.98	12.22	8.71	11.77
2023	1.66	1.28	2.27	2.05	1.32	6.53	7.02	21.70	7.95	11.09	5.85	12.52
2024	12.01	1.00	13.41	4.44	7.50	11.40	11.48	7.06	16.01	18.39	11.03	8.11
2025	3.86	0.90	2.61	1.87	4.30	8.19	9.64	8.52	17.99	14.77	23.15	8.01
2026	3.55	2.39	1.96	7.64	1.89	3.03	7.57	19.02	14.29	18.05	15.95	12.68
2027	3.10	2.11	5.99	1.06	0.06	3.27	9.52	11.30	11.98	15.37	17.29	11.04
2028	7.56	2.90	2.26	0.79	3.02	19.17	6.32	13.71	11.03	18.04	13.79	12.03
2029	9.11	6.10	0.73	3.03	3.81	0.33	20.57	10.93	17.44	22.94	7.09	4.96
2030	2.31	4.07	3.89	0.99	0.98	1.99	3.62	14.46	15.86	33.16	6.34	11.80
2031	6.24	2.01	1.61	0.44	4.20	3.77	13.18	11.80	22.09	12.84	9.00	11.27
2032	11.29	4.35	1.98	2.09	5.77	1.12	31.87	18.09	18.48	20.91	10.27	1.61
2033	0.79	1.27	2.35	4.23	0.80	0.45	4.08	7.39	28.49	11.38	7.57	6.48
2034	3.60	2.10	1.67	2.62	0.63	1.92	4.05	15.99	16.37	17.91	17.40	4.94
2035	11.61	2.04	9.01	0.50	6.59	5.30	5.89	4.12	20.39	13.94	12.75	13.18
2036	14.66	7.69	11.10	1.01	0.75	0.91	6.65	9.51	16.41	9.43	11.31	2.54
2037	2.08	14.37	2.18	2.45	0.06	2.27	8.49	31.30	11.27	12.62	8.17	3.75
2038	2.94	9.14	5.66	0.57	0.34	0.06	9.22	6.27	14.83	0.00	0.00	5.43
2039	1.83	3.50	0.23	3.67	2.73	2.71	1.31	11.04	7.94	14.07	12.62	9.34
2040	2.07	1.56	2.48	1.36	2.18	0.47	5.37	15.80	7.73	31.29	18.71	11.65
2041	9.50	2.47	2.15	14.96	2.53	2.19	6.82	14.28	16.29	18.68	11.55	5.12
2042	6.49	4.18	2.45	1.97	1.24	14.30	4.47	9.87	5.83	7.52	23.27	10.99
2043	6.27	0.28	5.49	3.91	0.14	3.60	11.68	1.27	11.13	12.13	13.83	6.96
2044	11.01	1.26	2.11	5.61	2.25	2.81	8.57	12.23	18.55	9.16	16.72	5.64
2045	4.04	3.11	0.57	0.15	2.22	1.32	6.84	20.84	10.64	17.49	15.14	5.32
2046	4.91	6.19	3.45	1.23	4.60	3.55	8.33	15.78	18.75	19.28	14.29	5.20
2047	10.44	9.66	2.75	3.63	4.27	3.52	2.73	10.36	13.65	24.34	11.25	24.06
2048	3.84	9.85	3.48	0.45	1.11	0.78	4.19	10.14	22.38	15.51	11.57	12.81
2049	5.84	12.55	1.26	0.33	3.66	2.33	5.35	22.04	13.44	8.93	6.99	2.92
2050	8.06	5.34	2.11	1.98	1.87	1.90	6.87	11.39	15.52	6.06	11.40	7.95
2051	5.55	5.17	2.79	1.98	1.87	1.90	8.83	7.99	12.35	18.57	18.48	10.21
2052	11.52	1.78	1.66	1.98	1.87	1.90	8.78	8.24	18.08	13.26	26.51	14.20
2053	7.89	10.63	1.66	3.91	1.87	3.82	5.02	11.37	21.83	14.01	15.40	5.99
2054	1.89	7.94	1.90	1.98	1.87	1.90	1.80	4.11	16.54	14.12	5.04	4.61
2055	1.89	1.78	1.66	1.98	1.87	5.46	8.21	4.71	13.22	24.00	8.98	5.72
2056	2.32	1.81	1.99	6.67	1.87	2.83	5.53	2.80	14.15	9.45	11.93	5.24
2057	6.58	5.52	2.67	2.17	2.57	3.33	8.01	12.15	16.69	9.50	12.11	10.63

RCP 4.5: Precipitation Data for 2058-2093 Period (% of MAP)												
Year	October	November	December	January	February	March	April	May	June	July	August	September
2058	6.07	5.88	7.29	1.48	9.38	5.07	2.47	24.53	21.87	13.18	8.76	12.40
2059	1.67	1.39	2.45	1.91	1.30	5.27	6.55	20.11	8.28	11.97	5.88	13.19
2060	12.10	1.09	14.46	4.12	7.39	9.19	10.70	6.54	16.69	19.83	11.09	8.55
2061	3.89	0.98	2.82	1.74	4.24	6.60	8.98	7.90	18.76	15.93	23.29	8.44
2062	3.57	2.58	2.11	7.10	1.86	2.44	7.05	17.63	14.90	19.47	16.04	13.36
2063	3.12	2.29	6.46	0.98	0.06	2.63	8.87	10.48	12.49	16.58	17.39	11.63
2064	7.62	3.14	2.44	0.73	2.98	15.45	5.89	12.71	11.50	19.46	13.87	12.67
2065	9.18	6.61	0.79	2.81	3.75	0.26	19.17	10.13	18.18	24.74	7.13	5.23
2066	2.32	4.41	4.20	0.92	0.96	1.61	3.38	13.59	16.54	35.76	6.37	12.43
2067	6.29	2.18	1.73	0.41	4.14	3.04	12.28	10.93	23.03	13.85	9.06	11.87
2068	11.38	4.71	2.13	1.94	5.69	0.91	29.70	16.77	19.26	22.56	10.33	1.70
2069	0.80	1.38	2.53	3.93	0.79	0.37	3.80	6.85	29.70	12.27	7.61	6.83
2070	3.62	2.28	1.80	2.43	0.62	1.55	3.78	14.82	17.07	19.32	17.50	5.21
2071	11.70	2.21	9.72	0.47	6.49	4.27	5.49	3.82	21.26	15.03	12.82	13.88
2072	14.77	8.32	11.97	0.94	0.73	0.73	6.20	8.82	17.11	10.17	11.37	2.68
2073	2.10	15.56	2.35	2.27	0.06	1.83	7.91	29.01	11.75	13.62	8.21	3.95
2074	2.96	9.90	6.10	0.52	0.33	0.05	8.59	5.81	15.46	0.00	0.00	5.72
2075	1.84	3.78	0.25	3.41	2.69	2.19	1.22	10.23	8.27	15.17	12.69	9.83
2076	2.09	1.69	2.67	1.26	2.15	0.38	5.01	14.64	8.06	33.74	18.82	12.27
2077	9.57	2.67	2.32	13.89	2.49	1.77	6.36	13.24	16.98	20.15	11.61	5.40
2078	6.54	4.52	2.64	1.83	1.22	11.53	4.16	9.15	6.07	8.11	23.40	11.57
2079	6.32	0.30	5.92	3.64	0.13	2.90	10.88	1.17	11.61	13.08	13.91	7.34
2080	11.10	1.37	2.28	5.21	2.21	2.27	7.98	11.34	19.34	9.88	16.81	5.94
2081	4.08	3.36	0.61	0.14	2.19	1.07	6.37	19.31	11.09	18.87	15.23	5.61
2082	4.95	6.71	3.72	1.15	4.53	2.86	7.77	14.62	19.55	20.79	14.37	5.48
2083	10.53	10.46	2.97	3.37	4.21	2.84	2.54	9.60	14.23	26.25	11.31	25.35
2084	3.87	10.67	3.75	0.42	1.10	0.63	3.91	9.39	23.34	16.72	11.63	13.49
2085	5.89	13.58	1.35	0.31	3.61	1.88	4.99	20.43	14.01	9.63	7.03	3.08
2086	8.12	5.78	2.27	1.84	1.84	1.54	6.40	10.56	16.18	6.53	11.47	8.38
2087	5.59	5.60	3.00	1.84	1.84	1.54	8.23	7.40	12.87	20.02	18.59	10.75
2088	11.61	1.93	1.79	1.84	1.84	1.54	8.18	7.64	18.85	14.30	26.67	14.96
2089	7.96	11.51	1.79	3.64	1.84	3.08	4.68	10.54	22.76	15.11	15.49	6.31
2090	1.90	8.59	2.05	1.84	1.84	1.54	1.68	3.81	17.25	15.23	5.07	4.86
2091	1.90	1.93	1.79	1.84	1.84	4.40	7.65	4.37	13.78	25.89	9.04	6.03
2092	2.33	1.96	2.15	6.19	1.84	2.28	5.15	2.60	14.75	10.19	12.00	5.52
2093	6.63	5.98	2.88	2.01	2.53	2.68	7.46	11.26	17.40	10.24	12.18	11.19

RCP 8.5

RCP 8.5: Precipitation Data for 2022-2057 Period (% of MAP)												
Year	**October**	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**
2022	5.98	5.81	7.34	1.69	9.59	6.37	2.75	27.41	20.83	12.14	8.80	11.99
2023	1.65	1.37	2.47	2.18	1.33	6.62	7.28	22.47	7.89	11.02	5.91	12.75
2024	11.92	1.07	14.57	4.71	7.55	11.55	11.90	7.31	15.90	18.26	11.15	8.27
2025	3.83	0.97	2.84	1.98	4.33	8.30	9.99	8.83	17.87	14.66	23.40	8.17
2026	3.52	2.55	2.13	8.11	1.90	3.07	7.84	19.70	14.19	17.92	16.12	12.92
2027	3.08	2.26	6.51	1.12	0.06	3.31	9.87	11.71	11.90	15.26	17.47	11.25
2028	7.51	3.11	2.46	0.84	3.04	19.43	6.55	14.20	10.95	17.91	13.94	12.25
2029	9.04	6.53	0.79	3.22	3.84	0.33	21.32	11.32	17.32	22.78	7.16	5.06
2030	2.29	4.36	4.23	1.05	0.99	2.02	3.76	15.18	15.75	32.92	6.41	12.02
2031	6.20	2.15	1.75	0.47	4.24	3.82	13.66	12.22	21.94	12.75	9.10	11.48
2032	11.22	4.65	2.15	2.21	5.82	1.14	33.03	18.74	18.35	20.77	10.39	1.64
2033	0.79	1.36	2.55	4.49	0.81	0.46	4.23	7.66	28.29	11.30	7.65	6.61
2034	3.57	2.25	1.81	2.78	0.63	1.95	4.20	16.57	16.26	17.79	17.59	5.04
2035	11.53	2.18	9.79	0.53	6.64	5.37	6.11	4.26	20.25	13.84	12.89	13.43
2036	14.55	8.22	12.06	1.07	0.75	0.92	6.89	9.85	16.30	9.36	11.43	2.59
2037	2.07	15.37	2.37	2.59	0.06	2.30	8.80	32.42	11.19	12.53	8.25	3.82
2038	2.92	9.78	6.15	0.60	0.34	0.06	9.56	6.49	14.72	0.00	0.00	5.54
2039	1.81	3.74	0.25	3.89	2.75	2.75	1.36	11.43	7.88	13.97	12.75	9.51
2040	2.06	1.67	2.69	1.44	2.20	0.48	5.57	16.36	7.68	31.07	18.91	11.87
2041	9.43	2.64	2.34	15.87	2.55	2.22	7.07	14.79	16.18	18.55	11.67	5.22
2042	6.54	4.52	2.64	1.83	1.22	11.53	4.16	9.15	6.07	8.11	23.40	11.57
2043	6.23	0.30	5.97	4.15	0.14	3.65	12.10	1.31	11.06	12.04	13.98	7.10
2044	10.93	1.35	2.30	5.95	2.26	2.85	8.88	12.67	18.42	9.09	16.90	5.75
2045	4.02	3.32	0.62	0.16	2.23	1.34	7.09	21.58	10.57	17.37	15.30	5.42
2046	4.88	6.62	3.75	1.31	4.64	3.60	8.64	16.34	18.62	19.14	14.45	5.30
2047	10.37	10.33	2.99	3.85	4.30	3.57	2.83	10.73	13.56	24.17	11.37	24.52
2048	3.81	10.54	3.78	0.48	1.12	0.79	4.35	10.50	22.23	15.40	11.69	13.05
2049	5.80	13.42	1.36	0.35	3.69	2.36	5.55	22.83	13.35	8.87	7.07	2.98
2050	8.00	5.71	2.29	2.10	1.88	1.93	7.12	11.80	15.41	6.02	11.53	8.11
2051	5.51	5.53	3.03	2.10	1.88	1.93	9.15	8.27	12.26	18.43	18.68	10.40
2052	11.44	1.90	1.80	2.10	1.88	1.93	9.10	8.54	17.95	13.16	26.80	14.47
2053	7.84	11.37	1.80	4.15	1.88	3.87	5.20	11.78	21.68	13.91	15.56	6.11
2054	1.87	8.49	2.06	2.10	1.88	1.93	1.87	4.25	16.43	14.02	5.09	4.70
2055	1.87	1.90	1.80	2.10	1.88	5.53	8.51	4.88	13.12	23.83	9.08	5.83
2056	2.30	1.93	2.17	7.07	1.88	2.87	5.73	2.90	14.05	9.38	12.06	5.34
2057	6.53	5.90	2.91	2.30	2.59	3.37	8.30	12.59	16.57	9.43	12.25	10.83

RCP 8.5: Precipitation Data for 2058-2093 Period (% of MAP)												
Year	October	November	December	January	February	March	April	May	June	July	August	September
2058	6.06	5.06	6.37	1.41	8.78	4.90	2.06	23.73	21.14	12.91	8.80	11.66
2059	1.67	1.19	2.14	1.82	1.21	5.09	5.46	19.46	8.01	11.72	5.91	12.41
2060	12.08	0.94	12.65	3.94	6.91	8.88	8.92	6.33	16.13	19.42	11.15	8.04
2061	3.88	0.84	2.46	1.66	3.96	6.38	7.49	7.64	18.13	15.60	23.40	7.94
2062	3.57	2.22	1.85	6.78	1.74	2.36	5.88	17.06	14.40	19.06	16.12	12.56
2063	3.12	1.97	5.65	0.94	0.05	2.55	7.40	10.14	12.07	16.23	17.48	10.94
2064	7.61	2.70	2.13	0.70	2.79	14.94	4.92	12.29	11.11	19.05	13.94	11.92
2065	9.16	5.68	0.69	2.69	3.51	0.25	15.99	9.80	17.57	24.23	7.17	4.92
2066	2.32	3.80	3.67	0.88	0.90	1.55	2.82	13.15	15.98	35.02	6.41	11.69
2067	6.28	1.87	1.52	0.39	3.88	2.94	10.25	10.58	22.26	13.56	9.10	11.17
2068	11.37	4.05	1.86	1.85	5.32	0.88	24.78	16.23	18.62	22.09	10.39	1.60
2069	0.80	1.18	2.21	3.76	0.74	0.35	3.17	6.63	28.70	12.02	7.65	6.43
2070	3.62	1.96	1.57	2.33	0.58	1.50	3.15	14.34	16.50	18.92	17.59	4.90
2071	11.68	1.90	8.50	0.45	6.07	4.13	4.58	3.69	20.55	14.72	12.89	13.06
2072	14.75	7.16	10.47	0.89	0.69	0.71	5.17	8.53	16.54	9.96	11.43	2.52
2073	2.09	13.39	2.06	2.17	0.05	1.77	6.60	28.07	11.36	13.33	8.26	3.72
2074	2.96	8.52	5.33	0.50	0.31	0.05	7.17	5.62	14.94	0.00	0.00	5.38
2075	1.84	3.25	0.22	3.26	2.52	2.11	1.02	9.90	8.00	14.86	12.75	9.25
2076	2.08	1.45	2.33	1.20	2.01	0.37	4.18	14.17	7.79	33.04	18.92	11.54
2077	9.56	2.30	2.03	13.28	2.33	1.71	5.30	12.81	16.41	19.73	11.67	5.08
2078	6.53	3.89	2.31	1.75	1.14	11.14	3.47	8.85	5.87	7.94	23.52	10.89
2079	6.31	0.26	5.18	3.47	0.13	2.81	9.08	1.14	11.22	12.81	13.98	6.90
2080	11.08	1.18	1.99	4.98	2.07	2.19	6.66	10.97	18.69	9.67	16.90	5.59
2081	4.07	2.89	0.54	0.14	2.04	1.03	5.32	18.68	10.72	18.48	15.30	5.28
2082	4.95	5.77	3.25	1.09	4.24	2.77	6.48	14.15	18.90	20.36	14.45	5.16
2083	10.51	9.00	2.59	3.22	3.94	2.75	2.12	9.29	13.75	25.71	11.37	23.85
2084	3.86	9.18	3.28	0.40	1.03	0.61	3.26	9.09	22.55	16.38	11.69	12.69
2085	5.88	11.69	1.18	0.29	3.38	1.81	4.16	19.77	13.54	9.43	7.07	2.90
2086	8.11	4.97	1.99	1.76	1.72	1.48	5.34	10.22	15.64	6.40	11.53	7.88
2087	5.59	4.82	2.63	1.76	1.72	1.48	6.86	7.16	12.44	19.61	18.68	10.12
2088	11.59	1.66	1.56	1.76	1.72	1.48	6.83	7.39	18.21	14.00	26.80	14.07
2089	7.94	9.90	1.56	3.47	1.72	2.98	3.90	10.20	21.99	14.79	15.57	5.94
2090	1.90	7.39	1.79	1.76	1.72	1.48	1.40	3.68	16.67	14.92	5.09	4.57
2091	1.90	1.66	1.56	1.76	1.72	4.25	6.38	4.23	13.32	25.35	9.08	5.67
2092	2.33	1.68	1.88	5.92	1.72	2.21	4.30	2.51	14.26	9.98	12.06	5.20
2093	6.62	5.14	2.52	1.92	2.37	2.59	6.22	10.90	16.82	10.03	12.25	10.53

Appendix G: Projected Municipal Water Abstractions under Development Scenarios

Low Development Scenario

Municipal Water Abstraction under Low Development Scenario (mcm)												
Year	October	November	December	January	February	March	April	May	June	July	August	September
2022	0.44	0.44	0.44	0.46	0.43	0.42	0.31	0.29	0.31	0.38	0.36	0.39
2023	0.45	0.45	0.45	0.47	0.44	0.43	0.32	0.30	0.32	0.39	0.37	0.40
2024	0.46	0.46	0.46	0.48	0.45	0.44	0.32	0.30	0.32	0.40	0.37	0.41
2025	0.47	0.47	0.47	0.49	0.46	0.45	0.33	0.31	0.33	0.40	0.38	0.41
2026	0.48	0.48	0.48	0.50	0.47	0.45	0.34	0.31	0.34	0.41	0.39	0.42
2027	0.49	0.49	0.49	0.51	0.47	0.46	0.34	0.32	0.34	0.42	0.40	0.43
2028	0.50	0.50	0.50	0.52	0.48	0.47	0.35	0.33	0.35	0.43	0.41	0.44
2029	0.51	0.51	0.51	0.53	0.49	0.48	0.36	0.33	0.36	0.44	0.41	0.45
2030	0.52	0.52	0.52	0.54	0.50	0.49	0.36	0.34	0.36	0.45	0.42	0.46
2031	0.53	0.53	0.53	0.55	0.51	0.50	0.37	0.35	0.37	0.45	0.43	0.47
2032	0.54	0.54	0.54	0.56	0.52	0.51	0.38	0.35	0.38	0.46	0.44	0.48
2033	0.55	0.55	0.55	0.57	0.53	0.52	0.39	0.36	0.39	0.47	0.45	0.48
2034	0.56	0.56	0.56	0.58	0.55	0.53	0.39	0.37	0.39	0.48	0.46	0.49
2035	0.57	0.57	0.57	0.60	0.56	0.54	0.40	0.38	0.40	0.49	0.47	0.50
2036	0.58	0.58	0.58	0.61	0.57	0.55	0.41	0.38	0.41	0.50	0.48	0.51
2037	0.59	0.59	0.59	0.62	0.58	0.57	0.42	0.39	0.42	0.51	0.48	0.52
2038	0.60	0.60	0.60	0.63	0.59	0.58	0.43	0.40	0.43	0.52	0.49	0.54
2039	0.62	0.62	0.62	0.64	0.60	0.59	0.43	0.41	0.43	0.53	0.50	0.55
2040	0.63	0.63	0.63	0.66	0.61	0.60	0.44	0.41	0.44	0.54	0.51	0.56
2041	0.64	0.64	0.64	0.67	0.63	0.61	0.45	0.42	0.45	0.55	0.52	0.57
2042	0.65	0.65	0.65	0.68	0.64	0.62	0.46	0.43	0.46	0.56	0.53	0.58
2043	0.67	0.67	0.67	0.70	0.65	0.64	0.47	0.44	0.47	0.58	0.55	0.59
2044	0.68	0.68	0.68	0.71	0.66	0.65	0.48	0.45	0.48	0.59	0.56	0.60
2045	0.69	0.69	0.69	0.73	0.68	0.66	0.49	0.46	0.49	0.60	0.57	0.61
2046	0.71	0.71	0.71	0.74	0.69	0.68	0.50	0.47	0.50	0.61	0.58	0.63
2047	0.72	0.72	0.72	0.75	0.71	0.69	0.51	0.48	0.51	0.62	0.59	0.64
2048	0.74	0.74	0.74	0.77	0.72	0.70	0.52	0.49	0.52	0.64	0.60	0.65
2049	0.75	0.75	0.75	0.79	0.73	0.72	0.53	0.49	0.53	0.65	0.61	0.67
2050	0.77	0.77	0.77	0.80	0.75	0.73	0.54	0.50	0.54	0.66	0.63	0.68
2051	0.78	0.78	0.78	0.82	0.76	0.75	0.55	0.51	0.55	0.67	0.64	0.69
2052	0.80	0.80	0.80	0.83	0.78	0.76	0.56	0.53	0.56	0.69	0.65	0.71
2053	0.81	0.81	0.81	0.85	0.79	0.78	0.57	0.54	0.57	0.70	0.67	0.72
2054	0.83	0.83	0.83	0.87	0.81	0.79	0.58	0.55	0.58	0.72	0.68	0.73
2055	0.85	0.85	0.85	0.88	0.83	0.81	0.60	0.56	0.60	0.73	0.69	0.75
2056	0.86	0.86	0.86	0.90	0.84	0.82	0.61	0.57	0.61	0.75	0.71	0.76
2057	0.88	0.88	0.88	0.92	0.86	0.84	0.62	0.58	0.62	0.76	0.72	0.78

High Development Scenario

Municipal Water Abstraction under High Development Scenario (mcm)												
Year	October	November	December	January	February	March	April	May	June	July	August	September
2022	0.44	0.44	0.44	0.46	0.43	0.42	0.31	0.29	0.31	0.38	0.36	0.39
2023	0.45	0.45	0.45	0.47	0.44	0.43	0.32	0.30	0.32	0.39	0.37	0.40
2024	0.47	0.47	0.47	0.49	0.46	0.45	0.33	0.31	0.33	0.40	0.38	0.41
2025	0.48	0.48	0.48	0.50	0.47	0.46	0.34	0.32	0.34	0.42	0.39	0.43
2026	0.50	0.50	0.50	0.52	0.48	0.47	0.35	0.33	0.35	0.43	0.41	0.44
2027	0.51	0.51	0.51	0.53	0.50	0.49	0.36	0.34	0.36	0.44	0.42	0.45
2028	0.53	0.53	0.53	0.55	0.51	0.50	0.37	0.35	0.37	0.45	0.43	0.47
2029	0.54	0.54	0.54	0.57	0.53	0.52	0.38	0.36	0.38	0.47	0.44	0.48
2030	0.56	0.56	0.56	0.58	0.54	0.53	0.39	0.37	0.39	0.48	0.46	0.49
2031	0.57	0.57	0.57	0.60	0.56	0.55	0.40	0.38	0.40	0.50	0.47	0.51
2032	0.59	0.59	0.59	0.62	0.58	0.56	0.42	0.39	0.42	0.51	0.48	0.52
2033	0.61	0.61	0.61	0.64	0.60	0.58	0.43	0.40	0.43	0.53	0.50	0.54
2034	0.63	0.63	0.63	0.66	0.61	0.60	0.44	0.41	0.44	0.54	0.51	0.56
2035	0.65	0.65	0.65	0.68	0.63	0.62	0.46	0.43	0.46	0.56	0.53	0.57
2036	0.67	0.67	0.67	0.70	0.65	0.64	0.47	0.44	0.47	0.57	0.54	0.59
2037	0.69	0.69	0.69	0.72	0.67	0.65	0.48	0.45	0.48	0.59	0.56	0.61
2038	0.71	0.71	0.71	0.74	0.69	0.67	0.50	0.47	0.50	0.61	0.58	0.63
2039	0.73	0.73	0.73	0.76	0.71	0.69	0.51	0.48	0.51	0.63	0.60	0.64
2040	0.75	0.75	0.75	0.78	0.73	0.72	0.53	0.49	0.53	0.65	0.61	0.66
2041	0.77	0.77	0.77	0.81	0.75	0.74	0.54	0.51	0.54	0.67	0.63	0.68
2042	0.79	0.79	0.79	0.83	0.78	0.76	0.56	0.52	0.56	0.69	0.65	0.70
2043	0.82	0.82	0.82	0.86	0.80	0.78	0.58	0.54	0.58	0.71	0.67	0.73
2044	0.84	0.84	0.84	0.88	0.82	0.80	0.59	0.56	0.59	0.73	0.69	0.75
2045	0.87	0.87	0.87	0.91	0.85	0.83	0.61	0.57	0.61	0.75	0.71	0.77
2046	0.89	0.89	0.89	0.94	0.87	0.85	0.63	0.59	0.63	0.77	0.73	0.79
2047	0.92	0.92	0.92	0.96	0.90	0.88	0.65	0.61	0.65	0.80	0.75	0.82
2048	0.95	0.95	0.95	0.99	0.93	0.91	0.67	0.63	0.67	0.82	0.78	0.84
2049	0.98	0.98	0.98	1.02	0.96	0.93	0.69	0.64	0.69	0.84	0.80	0.87
2050	1.01	1.01	1.01	1.05	0.98	0.96	0.71	0.66	0.71	0.87	0.82	0.89
2051	1.04	1.04	1.04	1.08	1.01	0.99	0.73	0.68	0.73	0.90	0.85	0.92
2052	1.07	1.07	1.07	1.12	1.04	1.02	0.75	0.70	0.75	0.92	0.87	0.95
2053	1.10	1.10	1.10	1.15	1.08	1.05	0.78	0.73	0.78	0.95	0.90	0.98
2054	1.13	1.13	1.13	1.18	1.11	1.08	0.80	0.75	0.80	0.98	0.93	1.00
2055	1.17	1.17	1.17	1.22	1.14	1.11	0.82	0.77	0.82	1.01	0.95	1.03
2056	1.20	1.20	1.20	1.26	1.17	1.15	0.85	0.79	0.85	1.04	0.98	1.07
2057	1.24	1.24	1.24	1.29	1.21	1.18	0.87	0.82	0.87	1.07	1.01	1.10

Appendix H: Projected Return Flows under Development Scenarios

Low Development Scenario

Return Flows under Low Development Scenario (Ml/day)												
Year	October	November	December	January	February	March	April	May	June	July	August	September
2022	0.599	0.516	0.492	0.469	0.495	0.544	0.518	0.536	0.585	0.688	0.709	0.632
2023	0.607	0.523	0.499	0.476	0.502	0.552	0.525	0.544	0.593	0.698	0.719	0.641
2024	0.616	0.531	0.506	0.482	0.509	0.560	0.533	0.551	0.602	0.708	0.729	0.650
2025	0.625	0.538	0.513	0.489	0.516	0.568	0.540	0.559	0.610	0.718	0.740	0.659
2026	0.634	0.546	0.521	0.496	0.524	0.576	0.548	0.567	0.619	0.728	0.750	0.669
2027	0.643	0.554	0.528	0.503	0.531	0.584	0.556	0.575	0.628	0.739	0.761	0.679
2028	0.652	0.562	0.536	0.511	0.539	0.592	0.564	0.584	0.637	0.749	0.772	0.688
2029	0.662	0.570	0.544	0.518	0.547	0.601	0.572	0.592	0.646	0.760	0.783	0.698
2030	0.672	0.579	0.552	0.526	0.555	0.610	0.581	0.601	0.656	0.771	0.795	0.709
2031	0.682	0.587	0.560	0.534	0.563	0.619	0.589	0.610	0.666	0.783	0.807	0.719
2032	0.692	0.596	0.568	0.541	0.572	0.628	0.598	0.619	0.675	0.794	0.819	0.730
2033	0.702	0.605	0.577	0.550	0.580	0.637	0.607	0.628	0.686	0.806	0.831	0.741
2034	0.712	0.614	0.585	0.558	0.589	0.647	0.616	0.638	0.696	0.818	0.843	0.752
2035	0.723	0.623	0.594	0.566	0.598	0.657	0.625	0.647	0.706	0.831	0.856	0.763
2036	0.734	0.633	0.603	0.575	0.607	0.667	0.635	0.657	0.717	0.843	0.869	0.775
2037	0.745	0.642	0.612	0.583	0.616	0.677	0.645	0.667	0.728	0.856	0.882	0.787
2038	0.757	0.652	0.622	0.592	0.625	0.687	0.654	0.677	0.739	0.869	0.896	0.799
2039	0.768	0.662	0.631	0.601	0.635	0.698	0.664	0.688	0.750	0.883	0.910	0.811
2040	0.780	0.672	0.641	0.611	0.645	0.708	0.675	0.698	0.762	0.896	0.924	0.823
2041	0.792	0.683	0.651	0.620	0.655	0.719	0.685	0.709	0.774	0.910	0.938	0.836
2042	0.805	0.693	0.661	0.630	0.665	0.731	0.696	0.720	0.786	0.924	0.952	0.849
2043	0.817	0.704	0.671	0.640	0.675	0.742	0.707	0.731	0.798	0.939	0.967	0.863
2044	0.830	0.715	0.682	0.650	0.686	0.754	0.718	0.743	0.810	0.953	0.983	0.876
2045	0.843	0.727	0.693	0.660	0.697	0.766	0.729	0.755	0.823	0.968	0.998	0.890
2046	0.856	0.738	0.704	0.670	0.708	0.778	0.741	0.767	0.836	0.984	1.014	0.904
2047	0.870	0.750	0.715	0.681	0.719	0.790	0.752	0.779	0.850	0.999	1.030	0.918
2048	0.884	0.762	0.726	0.692	0.731	0.803	0.764	0.791	0.863	1.015	1.046	0.933
2049	0.898	0.774	0.738	0.703	0.742	0.815	0.777	0.804	0.877	1.032	1.063	0.948
2050	0.912	0.786	0.750	0.714	0.754	0.829	0.789	0.817	0.891	1.048	1.080	0.963
2051	0.927	0.799	0.762	0.726	0.767	0.842	0.802	0.830	0.905	1.065	1.098	0.979
2052	0.942	0.812	0.774	0.738	0.779	0.856	0.815	0.844	0.920	1.082	1.115	0.995
2053	0.958	0.825	0.787	0.750	0.792	0.869	0.828	0.857	0.935	1.100	1.134	1.011
2054	0.973	0.839	0.800	0.762	0.805	0.884	0.842	0.871	0.950	1.118	1.152	1.027
2055	0.989	0.853	0.813	0.774	0.818	0.898	0.856	0.886	0.966	1.136	1.171	1.044
2056	1.005	0.867	0.826	0.787	0.831	0.913	0.870	0.900	0.982	1.155	1.190	1.061
2057	1.022	0.881	0.840	0.800	0.845	0.928	0.884	0.915	0.998	1.174	1.210	1.079

High Development Scenario

Return Flows under High Development Scenario (Ml/day)												
Year	October	November	December	January	February	March	April	May	June	July	August	September
2022	0.599	0.516	0.492	0.469	0.495	0.544	0.518	0.536	0.585	0.688	0.709	0.632
2023	0.612	0.527	0.502	0.479	0.506	0.556	0.529	0.547	0.597	0.703	0.724	0.645
2024	0.625	0.538	0.513	0.489	0.516	0.567	0.540	0.559	0.610	0.718	0.740	0.659
2025	0.638	0.550	0.524	0.500	0.527	0.580	0.552	0.571	0.623	0.733	0.755	0.673
2026	0.652	0.562	0.536	0.511	0.539	0.592	0.564	0.584	0.637	0.749	0.772	0.688
2027	0.666	0.574	0.547	0.522	0.551	0.605	0.576	0.596	0.651	0.765	0.789	0.703
2028	0.681	0.587	0.560	0.533	0.563	0.619	0.589	0.610	0.665	0.782	0.806	0.719
2029	0.696	0.600	0.572	0.545	0.575	0.632	0.602	0.623	0.680	0.800	0.824	0.735
2030	0.712	0.613	0.585	0.557	0.588	0.646	0.616	0.637	0.695	0.818	0.843	0.751
2031	0.728	0.627	0.598	0.570	0.602	0.661	0.630	0.652	0.711	0.836	0.862	0.768
2032	0.744	0.642	0.612	0.583	0.615	0.676	0.644	0.666	0.727	0.855	0.881	0.786
2033	0.762	0.656	0.626	0.596	0.629	0.692	0.659	0.682	0.744	0.875	0.902	0.804
2034	0.779	0.671	0.640	0.610	0.644	0.707	0.674	0.697	0.761	0.895	0.922	0.822
2035	0.797	0.687	0.655	0.624	0.659	0.724	0.689	0.714	0.779	0.916	0.944	0.841
2036	0.816	0.703	0.670	0.639	0.674	0.741	0.706	0.730	0.797	0.937	0.966	0.861
2037	0.835	0.720	0.686	0.654	0.690	0.758	0.722	0.747	0.815	0.959	0.989	0.881
2038	0.855	0.737	0.702	0.669	0.707	0.776	0.739	0.765	0.835	0.982	1.012	0.902
2039	0.875	0.754	0.719	0.685	0.723	0.795	0.757	0.783	0.855	1.005	1.036	0.924
2040	0.896	0.772	0.736	0.702	0.741	0.814	0.775	0.802	0.875	1.029	1.061	0.946
2041	0.918	0.791	0.754	0.718	0.759	0.833	0.794	0.822	0.896	1.054	1.087	0.969
2042	0.940	0.810	0.773	0.736	0.777	0.854	0.813	0.842	0.918	1.080	1.113	0.992
2043	0.963	0.830	0.791	0.754	0.796	0.874	0.833	0.862	0.940	1.106	1.140	1.017
2044	0.987	0.850	0.811	0.772	0.816	0.896	0.853	0.883	0.963	1.133	1.168	1.041
2045	1.011	0.871	0.831	0.791	0.836	0.918	0.874	0.905	0.987	1.161	1.197	1.067
2046	1.036	0.893	0.851	0.811	0.856	0.941	0.896	0.927	1.012	1.190	1.226	1.094
2047	1.062	0.915	0.873	0.831	0.878	0.964	0.918	0.951	1.037	1.220	1.257	1.121
2048	1.088	0.938	0.894	0.852	0.900	0.988	0.941	0.974	1.063	1.250	1.288	1.149
2049	1.116	0.962	0.917	0.873	0.922	1.013	0.965	0.999	1.089	1.282	1.321	1.178
2050	1.144	0.986	0.940	0.895	0.946	1.039	0.989	1.024	1.117	1.314	1.354	1.208
2051	1.173	1.011	0.964	0.918	0.970	1.065	1.015	1.050	1.145	1.347	1.389	1.238
2052	1.203	1.037	0.989	0.941	0.995	1.092	1.040	1.077	1.174	1.382	1.424	1.270
2053	1.234	1.064	1.014	0.966	1.020	1.120	1.067	1.105	1.205	1.417	1.461	1.303
2054	1.265	1.091	1.040	0.990	1.046	1.149	1.094	1.133	1.236	1.453	1.498	1.336
2055	1.298	1.119	1.067	1.016	1.073	1.178	1.123	1.162	1.267	1.491	1.537	1.371
2056	1.332	1.148	1.095	1.042	1.101	1.209	1.152	1.192	1.300	1.530	1.577	1.406
2057	1.366	1.178	1.123	1.069	1.130	1.241	1.182	1.223	1.334	1.570	1.618	1.443